ERDC/GSL TR-15-27

Geotechnical and Structures Laboratory

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*U.S. Air Force Airfield Damage Repair (ADR) Modernization Program*

# Large Crater Repair at Silver Flag Exercise Site, Tyndall Air Force Base, Florida

William D. Carruth, Lulu Edwards, Haley P. Bell, Jeb S. Tingle, Jonathon R. Griffin, and Craig A. Rutland

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*Geotechnical and Structures Laboratory*
*U.S. Army Engineer Research and Development Center*
*3909 Halls Ferry Road*
*Vicksburg, MS 39180-6199*

Dr. Craig A. Rutland

*Engineering Division*
Civil Engineering Branch
*Air Force Civil Engineering Center*
*139 Barnes Drive, Suite 1*
*Tyndall AFB, FL 32403*

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Under Airfield Damage Repair Modernization Program

# Abstract

The inability to effectively operate both fighter and heavy cargo aircraft on the same repaired runway after an attack poses significant operational challenges. The U.S. Air Force Air Combat Command (ACC) began the Airfield Damage Repair (ADR) Modernization Program to develop technologies to address operational limitations of current ADR equipment, material, and tactics. The objective of the program was to modernize the Air Force's ADR capability through development of new ADR solutions that are suitable for both fighter and cargo aircraft while scalable to the threat or damage. These solutions were successfully demonstrated as a part of the Critical Runway AssessmenT and Repair (CRATR) Joint Capabilities Technology Demonstration (JCTD) Program for small (8.5 ft by 8.5 ft) crater repairs. This report describes the use of new ADR technologies for repairing large (30 ft by 30 ft) craters at the Silver Flag Exercise Site in Tyndall Air Force Base, Florida. Modernized ADR technologies were successfully demonstrated in a series of three different large crater repairs. Two repairs utilized flowable fill backfill, while one used a crushed stone backfill. The repairs conducted using flowable fill backfill withstood 1,500 simulated C-17 aircraft passes before reaching failure, while the repair backfilled with crushed stone failed at 400 passes.

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# Preface

This study was conducted for Headquarters Air Force Civil Engineer Center, Tyndall AFB, Florida, under the Airfield Damage Repair Modernization Program. The Technical Monitor for this project was Dr. Craig Rutland of the Air Force Civil Engineer Center (AFCEC).

The work was performed by the Airfields and Pavements Branch (GMA) of the Engineering Systems and Materials Division (GM), U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Dr. John Rushing was Acting Chief, CEERD-GMA; Dr. Larry N. Lynch was Chief, CEERD-GM; and Nicholas Boone, CEERD-GVT, was the Technical Director for Force Projection and Maneuver Support. The Acting Deputy Director of ERDC-GSL was Dr. Gordon W. McMahon, and the Acting Director was Dr. William P. Grogan.

LTC John T. Tucker III was the Acting Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

# Definitions

For clarity, terms used in this report are defined as follows:

1. *Airfield damage repair (ADR):* Activities of engineer personnel in response to an attack on an airbase to provide adequate launch and recovery surfaces for the mission aircraft. Although ADR criteria were based on repairing airfields in friendly territory, recent military operations require repairing airbases occupied previously by hostile forces damaged during forcible entry or purposely sabotaged by departing forces. ADR encompasses other areas besides the repair of bomb damage including damage assessment, identification of candidate minimum operating strips, and the safe disposal of unexploded ordnance.

2. *Expedient repair:* Repairs conducted to create an initial operationally capable launch and recovery surface known as the minimum operating strip (MOS), based on projected mission aircraft requirements. These repairs are conducted in the most expeditious manner possible. When sufficient equipment and materials are available, individual crater repairs should be completed within 4 hr. Expedient repairs must provide an accessible and functional MOS that will sustain 100 passes of an F-15E aircraft with a gross weight of 35,235 lb.

3. *Sustainment repairs:* Repair efforts to upgrade expedient repairs for increased aircraft traffic. These repairs are conducted as soon as the operational tempo permits and are expected to support the operation of at least 5,000 passes of an F-15E aircraft with a gross weight of 35,235 lb, without requiring additional maintenance. For these repairs, quality control is more important than construction time to minimize maintenance and maintain operational tempo.

4. *Spall:* Breakdown of a repair or slab edge that does not extend vertically through the slab but intersects either a joint or edge at an angle. Spalls develop from localized overloading of the concrete that may originate in traffic loads, restraint of the concrete as it undergoes volume change, or durability problems. Severity levels are determined by length and FOD potential.

5. *Camouflet:* The resulting cavity in a deep underground burst when there is no rupture of the surface.

6. *Crater:* Damage that penetrates through the pavement surface into the underlying base and subgrade soil uplifting the surrounding pavement and ejecting soil, rock, and pavement debris around the impact area.

7. *Large crater:* Crater with an apparent diameter equal to or greater than 15 ft.

8. *Small crater:* Crater with an apparent diameter less than 15 ft.

9. *Rapid-setting material:* A cementitious material similar to portland cement concrete (PCC) but with high early compressive strengths and very fast set times. These materials typically contain finely ground ordinary portland cement (OPC) or modern hydrating materials such as magnesium phosphate or alumina.

10. *Pass:* One traverse of a load wheel across a given length of runway, taxiway, or test-section surface.

11. *Coverage:* One application of the load wheel over every single point in the central portion of the traffic lane. For a normally distributed traffic pattern, the test section pass-to-coverage ratio is determined by dividing the total number of passes in one pattern of traffic by the number of times the load wheel passes over the peak traffic lane. For a single-wheel aircraft gear, the number of coverages is simply the number of times the wheel travels down the center traffic lane in a five-lane distribution.

12. *Pattern:* The completion of one simulated normal distribution of traffic in a test lane by the test load cart.

13. *Subgrade:* An area of soil processed under controlled conditions to provide a desired bearing capacity upon which additional pavement layers are placed.

14. *Traffic lane:* The portion of the test section that is subjected to the moving load of the load cart.

15. *Load cart:* A specially constructed vehicle used in engineering tests for simulating aircraft taxiing operations.

16. *Test wheel:* The wheel on the load cart that supports the main load. In this test, the wheels are actual aircraft wheels mounted on the load cart.

17. *Elastic deformation:* Temporary vertical bending of the crater cap under the static load from the test wheel.

18. *Plastic/permanent deformation:* The permanent change in elevation of the cap resulting from load applications.

19. *California bearing ratio (CBR):* A soil strength index based upon its shearing resistance. The CBR value is calculated by dividing the unit load required to force a piston into the soil by the unit load required to force the same piston the same depth into a standard sample of crushed stone and multiplying by 100%.

# Unit Conversion Factors

| Multiply | By | To Obtain |
|---|---|---|
| cubic feet | 0.02831685 | cubic meters |
| cubic inch | 1.6387064 E-05 | cubic meters |
| cubic yards | 0.7645549 | cubic meters |
| degrees (angle) | 0.01745329 | radians |
| degrees Fahrenheit | (F-32)/1.8 | degrees Celsius |
| feet | 0.3048 | meters |
| gallons (U.S. liquid) | 3.785412 E-03 | cubic meters |
| inch | 0.0254 | meters |
| ounces (U.S. fluid) | 2.957353 E-05 | cubic meters |
| pounds (force) | 4.448222 | newtons |
| pounds (force) per square inch | 6.894757 | kilopascals |
| pounds (mass) | 0.45359237 | kilograms |
| pounds (mass) per cubic foot | 16.01846 | kilograms per cubic meter |
| square feet | 0.09290304 | square meters |
| square inch | 6.4516 E-04 | square meters |
| tons (2,000 pounds, mass) | 907.1847 | kilograms |
| yards | 0.9144 | meters |

# 1 Introduction

## 1.1 Background

In March 2002, the Joint Airfield Damage Repair Working Group identified the lack of certification of existing airfield damage repair (ADR) methods for C-17 aircraft as the number one issue requiring immediate attention. The U.S. Air Force (USAF) Air Mobility Command funded the U.S. Army Engineer Research and Development Center (ERDC) to evaluate existing ADR expedient repair technologies under C-17 aircraft loads. The ERDC testing produced the following conclusions (Gartrell 2007; Gartrell 2008):

1. Load cart testing verified that the legacy expedient repair systems provide adequate vertical load bearing support for current aircraft.
2. New anchor bolts were developed and recommended for anchoring current foreign object debris (FOD) cover mats to concrete pavements.
3. Maximum allowable roughness limits were determined for the C-17 aircraft using available computer models. The limits determined the maximum allowable sag across repaired craters to prevent exceeding design limits of the aircraft gear.

In 2005, the ERDC and the C-17 Systems Group conducted flight tests on the legacy expedient repair technologies at Plant 42 in Palmdale, Calif. The following results were observed:

1. The current USAF technology consisting of a crushed stone backfill surfaced with folded fiberglass mat (FFM) survived medium-speed braking events and was deemed suitable for use on taxiways and aprons.
2. The current USAF FFM system failed under high-speed taxi events due to the formation of a bow wave and the subsequent failure of the fiberglass mat component of the system.
3. The U.S. Army system consisting of a sand grid-reinforced backfill surfaced with fiberglass-reinforced polyester (FRP) panels failed under medium-speed braking events due to failure of the connector bushings. After replacement with more robust connector bushings from the FFM system, the FRP system withstood the high-speed taxi events that caused the FFM to fail.

4. AM2 aluminum matting was successfully tested as a suitable expedient ADR technology for taxiways and aprons, but cannot be used on runway surfaces due to the potential roughness associated with its inherent profile thickness.

The most significant shortfall noted from the evaluation of the legacy ADR expedient repair technologies was that none of the repair technologies was capable of supporting C-17 aircraft on a runway where high, horizontal braking forces cause the systems to fail. For C-17 operations only, the repairs can be performed without the protective mat surfacing or FOD cover. However, protective surfacing or FOD covers are required for fighter aircraft operations. Thus, the legacy repair technologies cannot be used on airfields subjected to both fighter and heavy cargo aircraft, due to the inability of the current systems to sustain C-17 operations and the inability of fighter aircraft to operate on unsurfaced repairs.

In 2006, the U.S. Department of Defense (DOD) Pacific Command (PACOM) identified a new threat scenario that revealed further operational shortfalls. Traditional ADR activities focused on the repair of a few large craters in a short time period. However, evolving threat scenarios have identified the potential for a large number of smaller craters based upon specific weapon analyses. Legacy technologies were designed to address a large number of small craters and were unlikely to meet the operational requirements of those threat scenarios. Thus, new technologies were required to address the full spectrum of operational scenarios that could potentially be encountered in different theaters of operation. In response to this need, the Critical Runway AssessmenT and Repair (CRATR) Joint Capabilities Technology Demonstration (JCTD) Program was initiated.

The CRATR JCTD Program intended to provide a method of rapidly assessing and repairing damage to an airfield. The JCTD program's goal was to develop capabilities to return damaged runways (repairing up to 100 small craters) to full operational sortie production in less than 8 hr. The CRATR JCTD included three major technology demonstrations: two limited operational utility assessments (LOUAs) and one operational utility assessment (OUA). LOUA1 was conducted at the Silver Flag Exercise site, Tyndall AFB, Florida, during August through October 2008 (Tingle et al. 2009). LOUA1 was conducted to evaluate tactics, techniques, and procedures (TTPs), materials, and prototype equipment for rapid

automated airfield assessment and crater repair. General conclusions and recommendations from LOUA1 are summarized below:

1. The addition of multi-terrain loaders (MTLs) to ADR equipment packages was recommended due to maneuverability in confined locations and versatility in performing many ADR tasks.
2. A combination of a MTL with a wheel saw such as the Caterpillar 277C with a Caterpillar SW45 was very successful in saw cutting upheaved pavement sections.
3. The Caterpillar M322D and the Volvo EW180C excavators both proved to be suitable for excavation purposes. A larger area plate compactor attachment for either excavator was recommended for compacting granular backfill.
4. Expandable foam backfill performed well under traffic tests when surfaced with rapid-setting cementitious caps; however, the foam required reformulation to increase pot life and reduce water sensitivity.
5. It was recommended that the foam dispenser prototype be redesigned to improve the ease of operation, uniformity of foam distribution, and maintenance activities. The production capacity of the foam dispenser needed to be variable and increased by as much as 500%.
6. The rapid-setting cementitious materials performed well under traffic tests.
7. Based on evaluation of several mixer configurations, recommendations were to develop a simplified volumetric mixer that could be factory calibrated to several rapid-setting materials.
8. Based on evaluation of a pelletized asphalt concrete (AC) dispenser and material, recommendations were to increase production capacity of the mixer and improve packaging and loading of materials.
9. The pelletized AC performed well under traffic tests but required improved placement techniques.
10. The modified FRP and anchoring systems performed well during the demonstration, given its intended purpose of withstanding expedient pass levels of 100. The repairs did not meet the CRATR JCTD objective of 900 to 3,000 passes of combined heavy and fighter traffic.
11. The isolation of individual tasks during LOUA1 obscured the true timeline for completion of the entire repair. This method did not consider efficiencies in working from beginning to end on a single crater and resulted in unrealistic total repair times when the times for each task were simply summed. It was anticipated that additional efficiency would be achieved after the specialized equipment was refined and added to

inventory, the units are properly trained in the methods used, and the employment procedures are refined for maximum efficiency.

Following material and equipment modifications, LOUA2 was conducted at the Silver Flag Exercise site, Tyndall AFB, during April 2009 (Priddy et al. 2013). LOUA2 was conducted to further evaluate materials, TTPs, and prototype equipment for crater repair. General conclusions and recommendations from LOUA2 are summarized below:

1. MTLs and wheeled excavators with multiple attachments continued to show versatility in multiple ADR tasks and maneuverability in confined locations.
2. A combination of a MTL with a wheel saw such as the Caterpillar 277C with a Caterpillar SW45 was successful in both thick and thin pavements for removing upheaved pavement sections.
3. Following reformulation, the modified expandable foam backfill performed well under traffic tests when surfaced with rapid-setting cementitious caps.
4. Modifications to the foam dispenser provided easier operation, and increased dispenser rates reduced the time required to backfill each crater. Modification to the foam and the foam dispenser provided more uniform rise of foam backfill. Additional modifications to the foam dispenser were recommended to eliminate the requirement for a separate flushing system for maintenance activities.
5. Rapid-setting flowable fill provided an alternative to compacted soil or aggregates and expandable foam for backfilling damaged pavements. Placed dry, the material did not require mechanical mixing and performed well during traffic tests when surfaced with rapid-setting concrete caps. When placed wet, the material performed well under AC caps.
6. Based on recommendations from LOUA1, the simplified volumetric mixer was successfully factory calibrated for several rapid-setting materials. Simultaneous loading and dispensing of material reduced the time required to place rapid-setting cementitious caps. Recommendations to improve the system included increasing the capacity of the onboard water tanks, improving the maneuverability of the equipment, and providing easier loading of materials.
7. Following redesign and reformulation, the pelletized AC mixer successfully produced small batches of hot-mix asphalt that could be rapidly graded and compacted for airfield surfaces.

Successfully demonstrated technologies from LOUA2 were selected for a final OUA Demonstration. The OUA demonstration was conducted at Avon Park Air Force Range, Florida, during August 2009 (Priddy et al. 2013). The OUA was conducted to further refine the materials, TTPs, and prototype equipment for crater repair. General conclusions and recommendations from the OUA are summarized below:

1. The CRATR method TTPs developed for rapid-setting and pelletized AC-capped repairs were adequate to accomplish the ADR repair mission. Repair sequences that did not meet the 6.5-hr return to service requirement were due to equipment failures and lightning delays. The repair sequence and team breakdown/flow worked well for all sequences.
2. Communication between the crater chief and haul team is vital to the prompt delivery and unloading of materials and the completion of repair activities.
3. The Caterpillar SW45 wheel saw attachment worked well for thick and thin PCC when dowel bars were not encountered. However, a standard walk-behind concrete saw was helpful when cutting through dowels in concrete pavement.
4. In regard to excavation, debris should be kept as large as possible to prevent delays in excavation. Additionally, switching attachments for an excavator resulted in delays in performing repair tasks.
5. Buildup of rapid-setting material near the conveyor of the volumetric mixer should be promptly removed following use. Care is required when filling the wash out tank to prevent moisture from getting into the hopper.
6. Excess mix water in rapid-setting caps resulted in longer finishing times and increased labor to maintain runway crown. This also creates a high FOD potential if not immediately removed. Excessive finishing of the rapid-setting caps with the vibratory screed will also result in an overworked surface (i.e., shrinkage cracking) and weakened edges. Care must be taken to prevent feathering the edges of the crater caps to avoid FOD potential.

In general, the OUA demonstration validated that the new materials, equipment, and procedures are capable of meeting the required ADR timeline and sustaining aircraft traffic. Based on the results of the OUA, the decision to begin refinement and procurement of the new ADR technologies was made by the USAF.

## 1.2 Objective

The objective of the testing described in this report was to evaluate the suitability of the new repair materials, equipment, and methods to repair large craters up to 30 ft in diameter. The evaluation of the new ADR technologies for large craters was conducted to identify modifications to the materials, equipment, or procedures prior to the procurement of the new technologies to ensure satisfactory performance.

The new ADR technologies are required to support the repair of up to 120 small craters or 12 large craters (30 ft by 30 ft) on runway and taxiway surfaces within 3 hr (objective) or 6.5 hr (threshold) after an attack. The repairs are to be completed with flush surfaces to support designated aircraft types (i.e., transports, fighters, tankers).

## 1.3 Scope

Full-scale tests were conducted to complete crater repairs using rapid-setting concrete caps over both flowable fill and crushed stone backfill. The tests consisted of training USAF Prime BEEF and RED HORSE troops to use the new materials, equipment, and methods for crater repair and then performing three crater repairs under timed conditions. Two repairs were performed with flowable fill as the backfill, and crushed stone was used for one repair. The technologies evaluated during the large crater tests included:

1. Previously identified equipment solutions for rapidly removing upheaved pavement and debris from large bomb craters including wheel-saw attachments for compact track loaders (CTLs) and modern wheeled excavators with selected attachments,
2. Rapid-setting flowable fill to rapidly backfill large craters and provide uniform load support of the capping material,
3. Use of crushed stone as a backfill material to compare the manpower and time requirements with a rapid-setting flowable fill backfill for large craters,
4. Rapid-setting cementitious capping materials that are mixed and placed similar to ordinary concrete, with the exception that they harden within minutes and can sustain heavy aircraft traffic within 2 hr for large crater repairs, and
5. Simplified volumetric mixer for blending and placing rapid-setting cementitious backfill and capping material for large craters.

After completion of the repairs, each crater was trafficked using the C-17 load cart in a normally distributed traffic pattern. The craters were visually evaluated for damage at specific intervals during trafficking.

## 1.4 Outline of chapters

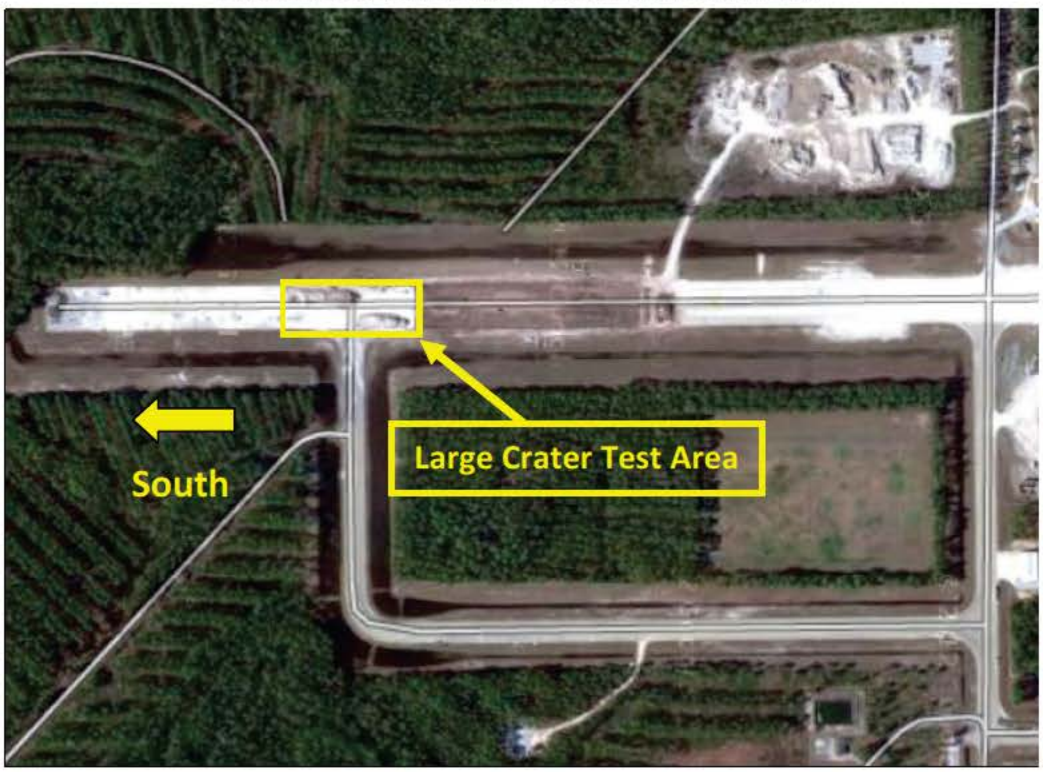
Chapter 1 provides background information covering the history of the ADR program and the specific objectives and scope of the work covered in this report. Chapter 2 presents a description of the test site and describes all equipment and materials used during testing. Chapter 3 provides a description of the teams and the repair processes. Chapter 4 discusses details of the training procedure and discusses test results obtained during training. Chapter 5 describes the large crater tests, including the layout, weather conditions, timeline, and results. Analysis of the results is also located in Chapter 5. Conclusions and lessons learned are described in Chapter 6. References used in preparing this report are also provided.

# 2 Test Site, Equipment, and Material Description

## 2.1 Test site description

The large crater repair testing took place during September 2012 at the Silver Flag Exercise Site on Tyndall AFB, Florida. An aerial photo of the test site is displayed in Figure 1. The test site was selected, because it is a training airfield with adequate PCC pavement thickness. The PCC thickness varied within the test area between 9 and 12 in. and, in general, the slabs were 15 ft by 15 ft.

Figure 1. Test site location – Silver Flag Exercise Site.




## 2.2 Equipment

### 2.2.1 Utility vehicles

Utility vehicles (UTVs) were used to transport team members, tools, and equipment as shown in Figure 2. The crater chief used a UTV for transport and to haul tape measures, shovels, rakes, brooms, paint, utility knives,

and extra personal protective equipment (PPE). The marking team used two UTVs to carry the marking and backfill equipment, while the spotters for the sawing and excavation teams used one UTV for transport.

Figure 2. Utility vehicle used for transporting team members and tools.

### 2.2.2 Stanchions

Stanchions, shown in Figure 3, were used in the crater profile measurement (CPM) process to determine the extent of upheaval around a crater. Two "T" stanchions, a sight rod, straight edge, and spray paint were used for the CPM process. More information about the stanchion construction and CPM process can be found in T.O. 35E2-5-1 (Air Force, 1992).

Figure 3. Stanchions used during training.

### 2.2.3 Caterpillar 279C Compact Track Loader

Caterpillar 279C Compact Track Loaders (CTLs), or skid steers, are high-flow, rubber-tracked machines with quick-disconnect fittings that are used extensively in the modernized ADR process. The quick disconnect allows attachments to be switched out rapidly without the use of tools. Specifications for the machine can be found in Table 1.

The track loaders are multi-purpose machines that are employed for rapidly cutting around the upheaval using wheel saw attachments, removing debris using the bucket attachments, or cleaning up with the broom attachments. The 279C CTL with the wheel saw attachment is shown in Figure 4.

Table 1. Caterpillar 279C CTL specifications.

| | |
|---|---|
| Net power | 82 hp |
| Operating weight | 9,495 lb |
| Rated operating capacity | 3,200 lb at 50% tipping load |
| Travel speed | 5.0 mph |
| Tipping load | 6,483 lb |
| Breakout force, tilt cylinder | 7,308 lb |
| Maximum loader hydraulic pressure[a] | 4,061 psi |
| Maximum loader hydraulic flow[a] | 33 gal/min |

[a] For high flow XPS models

Figure 4. Tracked Caterpillar 279C CTL with SW45 wheel saw attachment.


*2.2.3.1 Caterpillar SW45 and SW60 wheel saw attachments*

The CTLs are equipped to operate the Caterpillar SW45 and/or SW60 wheel saw attachments (shown in Figure 4). The wheel saw attachments used for crater repair provide a 3.5-in.-wide cut. The SW45 has an 18-in. maximum depth cut, and the SW60 has a 24-in. maximum depth cut. The wheel saws are equipped with a hydraulic side-shift (26 in. center to center) to assist in wheel positioning. The SW60 is a custom wheel saw that has been modified for ERDC. Commercial off-the-shelf (COTS) SW60 models have a 6-in.-wide blade, but this cut was too wide for the purposes of this program. The SW60 was modified to provide a 3.5-in.-wide cut and is now commercially available as the Caterpillar SW360B. Specifications for both machines can be found in Table 2.

During recent equipment testing conducted at ERDC, the Caterpillar 149-5763 teeth were determined to be the most efficient teeth to use for saw-cutting portland cement concrete (PCC) (Bell et al. 2014). These teeth are classified as cold planer teeth and are not the concrete teeth normally sold for the wheel saws. The conical bits, or teeth, used on the SW45 and SW60 for cutting are made with a carbide tip specifically designed for milling concrete, solid limestone, and ultra-hard rock (Figure 5). There are 64 teeth needed for the SW45 and 70 teeth needed for the SW60.

Table 2. Wheel saw specifications.

| | Caterpillar SW45 | Caterpillar SW60 |
|---|---|---|
| Overall width | 71 in. | 74 in. |
| Overall height | 57 in. | 69 in. |
| Length | 78 in. | 88 in. |
| Weight | 2,295 lb | 2,628 lb |
| Wheel width | 3.5 in. | 3.5 in. |
| Required hydraulic flow range | 24-42 gpm | 26-42 gpm |
| Optimal hydraulic pressure range | 2,611-4,351 psi | 2,611-4,351 psi |
| Wheel torque at maximum pressure | 4,944 lb•ft | 5931 lb•ft |
| Wheel speed at maximum flow | 115 rpm | 96 rpm |
| Number of teeth | 64 per wheel | 70 per wheel |
| Maximum depth of cut | 18 in. | 24 in. |
| Sideshift travel | 26 in. | 26 in. |

Figure 5. Replacing wheel saw teeth; inset shows close up of wheel saw teeth.


Replacing teeth is necessary when the carbide bits are worn. A punch tool is used with a mallet to remove the teeth, and the teeth are tapped in place with the mallet, as shown in Figure 5. Teeth were replaced prior to training and also prior to the start of each test.

### 2.2.3.2 *Bucket and broom attachments*

Caterpillar Bucket and BA18 broom attachments (Figure 6) for the Caterpillar 279C CTLs were used for debris removal and cleanup before, during, and/or after each crater repair test.

Figure 6. Bucket (left) and broom (right) attachments for Caterpillar 279C terrain loader.


### 2.2.3.3 *Vibratory roller attachment*

The Caterpillar CV18B vibratory roller attachment (Figure 7) for the Caterpillar 279C CTL was utilized to compact the subgrade before backfill placement and to compact crushed stone backfill, which was used for one of the test craters. Specifications for the CV18B attachment can be found in Table 3.

Figure 7. Caterpillar CV18B roller attached to Caterpillar 279C CTL.

Table 3. Caterpillar CV18B roller attachment specifications.

| | |
|---|---|
| Drum Width | 73 in. |
| Drum Diameter | 25 in. |
| Height | 2,946 vibrations/minute |
| Weight | 2,127 lb |
| Dynamic Force | 11,903 lb |
| Drum Oscillation Tilt Range +/- | 15 degrees |
| Amplitude | 0.043 in |
| Hydraulic Flow Range | 11-22 gal/min |
| Hydraulic Pressure Range | 2,100-3,400 psi |

### 2.2.4 Wheel saw targets and rulers

Prior to aligning the wheel saws, the desired cut depth was set by using the depth guide on the wheel saw (Figure 8). Rulers attached to the bottom of each wheel saw and magnetic arrows were used to help the spotter line up the wheel saw at the start of a cut to avoid unnecessary overcuts. As the wheel saw plunges into the pavement, it slowly moves back, which is why the ruler appears to place the wheel saw too far inside the marked crater. To align the saw, the spotter simply moves the arrow to the number on the ruler that corresponds to the approximate pavement thickness. The tip of the arrow should be lined up at the edge or corner of the marked repair. The use of wheel saw targets and rulers eliminated the need for extra spotters and decreased the potential for excessive overcuts during saw-cutting crater repairs. Figure 9 shows the ruler and arrow on the bottom of the wheel saw attachment.

For the 9-in.-thick PCC, the wheel saw targets were placed approximately one target base length (~16 in.) from the edge or corner of the repair. The CTL operator used the rookie stick bolted to the wheel saw attachment as a guide to line up with the target that the wheel saw spotter has placed at the end of the required cut. Once the wheel saw attachment bumps the target, the cut is complete. The targets eliminate the need for an additional spotter, as the single spotter is able to guide both CTL operators cutting around one corner of a crater. Figure 10 shows the targets near the end of the wheel saw repair cuts.

Figure 8. Ruler on top of wheel saw for lowering and raising guard according to desired cut depth.


Figure 9. Ruler for lining up wheel saw according to pavement thickness or cut depth.

Figure 10. Wheel saw target.


### 2.2.5 Husqvarna FS 6600D saw

The Husqvarna FS 6600D saw (Figure 11) is employed in the modernized ADR procedure, when dowels are encountered in the removal of damaged pavement or as a backup if a wheel saw is damaged and inoperable. The self-propelled, walk-behind saw is equipped with a 42-in.-diameter diamond blade. The Husqvarna saw is propelled by a John Deere motor with 66 hp and weighs 1,892 lb. The maximum cutting depth is 17.5 in. An external water supply is required to operate the saw. The walk-behind saw was not used during training or testing, because no newer dowels were present in the PCC. Older dowels were encountered, but the wheel saw attachments for the CTLs were capable of cutting through them.

### 2.2.6 Wheeled excavator

Wheeled excavators are preferred over tracked excavators for crater repair purposes, because they are more mobile and do not cause damage to the airfield pavement. Both the Volvo EW180C and Caterpillar M318D wheeled excavators were used during training and testing. Specifications for the Volvo EW180C and Volvo HB1400 hammer attachment are listed in Table 4 and Table 5, respectively. Specifications for the Caterpillar M318D and its hammer attachment, Caterpillar H120E, are also included in these tables. The excavators were equipped with quick-disconnect fittings for the hammer and bucket work tool attachments.

Figure 11. Husqvarna FS 6600D walk-behind saw with 42-in.-diameter blade.

Table 4. Excavator specifications.

| | Volvo EW 180C | Caterpillar M318D |
|---|---|---|
| Net power | 152 hp | 166 hp |
| Maximum torque | 538 lb•ft at 1,400 rpm | 596 lb•ft at 1,400 rpm |
| Breakout force | 24,998 lbf | 28,326 lbf |
| Maximum digging reach | 31.8 ft | 31.5 ft |
| Maximum digging depth | 20.8 ft | 20.9 ft |
| Maximum travel speed | 22 mph | 23 mph |
| Operating weight | 36,200 to 40,600 lb | 40,124 to 44,313 lb |

Table 5. Excavator hammer specifications.

| | Volvo HB 1400 | Caterpillar H120E |
|---|---|---|
| Impact energy | 2,500 lb•ft | 3,000 lb•ft |
| Operating weight | 2,932 lb | 3,476 lb |
| Tool diameter | 4.92 in. | 4.7 in. |
| Acceptable oil flows | 32 to 45 gpm | 26 to 45 gpm |
| Oil pressure | 1,958 to 2,103 psi | 2,175 psi |
| Impact rate | 450 to 800 blows per min | 350 to 620 blows per min |
| Excavator weight limits | 39,683 to 57,320 lb | 27,400 to 57,200 lb |

The Volvo HB1400 hammer with a chisel tip attached to a Volvo EW180C (Figure 12) wheeled excavator was used to break the PCC during the training and testing. Another Volvo EW180C wheeled excavator was mounted with a 42-in.-wide toothed bucket with thumb (Figure 13) for removing the broken PCC and base course material. The teeth on the bucket were 8.0 in. long.

Figure 12. Volvo EW180C excavator with HB1400 hammer.


Figure 13. Volvo EW180C excavator with 42-in.-wide bucket.

The Caterpillar M318D with hammer attachment (Figure 14) was also used to break PCC pavement prior to excavation. Although it was not used during training or testing, the M318D can also be equipped with a bucket attachment for excavation to be used interchangeably with the Volvo EW180C.

Figure 14. Caterpillar M318D excavator with H120E hammer attachment.


### 2.2.7 Caterpillar front-end loader

A front-end loader with a 2.5-$yd^3$ bucket was used for debris removal, subgrade and backfill preparation, and cleanup (Figure 15). The front-end loader used was a Caterpillar 924H with a Cat® C6.6 engine, 138 hp at a rated rpm of 1,800. The operating weight was 25,644 lb, static tipping load was 16,041 lb, and reach during a full lift at a 45° dump angle was 3.25 ft.

Figure 15. Caterpillar 924H front-end loader.

### 2.2.8 Small compaction equipment

A standard plate compactor was used periodically during training and testing to compact the edges of the excavation when preparing the natural subgrade and crushed stone backfill. The plate compactor used was a Wacker WP 1550W (Figure 16), which has a 6.0-hp motor capable of providing 3,375 lb of impact force. Due to the diameter of the drum, the CV18 compactor attachment could not achieve compaction next to the walls of the crater; thus, the small plate compactor was used to compact materials around the perimeter of the crater adjacent to the crater walls.

Figure 16. Wacker WP 1550W plate compactor.

### 2.2.9 Extendable-boom forklift

An extendable-boom forklift was used to transport the 3,000-lb super sacks of pre-blended flowable fill and rapid-setting concrete materials (Figure 17). The extendable boom was a Caterpillar TL642 telescopic forklift, which was capable of lifting 6,500 lb and extending 30 ft. The extendable boom is needed so that the large super sacks of cementitious material can be maneuvered around the repair site or loaded into the simplified volumetric concrete mixer.

Figure 17. Caterpillar TL642 extendable-boom forklift.


### 2.2.10 Tractor and lowboy trailer

A lowboy trailer (Figure 18) was used to transport 3,000-lb super sacks containing flowable fill and rapid-setting concrete materials to the repair area. A standard lowboy trailer is capable of transporting 14 super sacks from the dry storage area to the repair site. Material was off-loaded with extendable-boom forklifts and staged near the minimum operating strip (MOS) for loading rapid-setting concrete into the volumetric mixer or flowable fill directly into the excavation. The geotextile roll and concrete forms were also carried by the lowboy trailer and staged near the crater repair site. The forms were too large to be carried by the utility vehicles.

Figure 18. Supersacks and geotextile roll loaded on lowboy trailer.


### 2.2.11 Simplified volumetric concrete mixer

A specially designed tow-behind simplified volumetric concrete mixer (Figure 19) was designed by CemenTech Inc. in consultation with the ERDC. The simplified volumetric mixer is pre-calibrated for rapid-setting cementitious repair materials to include flowable fill and rigid capping material.

Figure 19. Simplified volumetric mixer towed by a dump truck.

The mixer is towed with a vehicle capable of pulling at least 20 tons. The mixer consists of a single dry-material hopper with a capacity of approximately 6 $yd^3$, a conveyor belt feed system, a positive displacement water pump to meter the mix water according to a fixed pump speed, two 200-gal water tanks on each side of the mixer, a liquid admixture container, a washout tank with pressure washer, and a replaceable mixing auger mounted in a discharge boom at the rear of the machine. The machine is outfitted with two retractable catwalk platforms, a bin entry platform, a replacement auger, and two super sack piercing points. The only means of controlling the water-cement (w/c) ratio is by adjusting a gate, which can change the height of the dry material on the conveyor belt feeding the mix auger. Allowing more dry material to enter the mix auger results in a mix with a lower w/c ratio. The wheel for adjusting the gate height has a scale from 1 to 12, where 1 allows the least amount of material to enter the mix auger and 12 allows the most.

### 2.2.12 Magnesium screed bar

The repairs were struck off using a 16-ft magnesium screed bar. The screed was moved across the repair with two personnel applying pressure at each end and using a sawing motion back and forth to ensure that the repair was level. Minimal hand finishing was performed after screeding using aluminum or magnesium hand tools. Finishing of the rapid-setting concrete is discussed further in Section 3.8.

### 2.2.13 Plastic concrete forms

Plastic, reusable concrete forms (Figure 20) were used to divide the large crater excavation into quadrants small enough to make placement of the rapid-setting concrete cap easier. The forms were manufactured by Poly Meta Forms®, and were constructed by stacking two 4-in.-tall forms on top of one another and connecting them via a stacking pocket that connects the two forms together, creating an 8-in.-tall form. Form pins were used along the length of the form to provide structural support for the rapid-setting concrete during placement.

### 2.2.14 Dump truck

A standard 12-ton dump truck was used for hauling crushed stone backfill to the repair site and towing the simplified volumetric mixer. Figure 21 shows the dump truck unloading crushed stone backfill into an excavated crater.

Figure 20. Plastic concrete forms.

Figure 21. Dump truck unloading crushed stone backfill.

### 2.2.15 Water truck

Two commercial water trucks (Figure 22) with a 2,000-gal capacity were needed for the backfilling and capping processes. Water is needed for placing dry flowable fill and for adding water to the volumetric mixer's saddle tanks to produce rapid-setting concrete. A 2-in. hose connection is used to carry out the process. The water trucks are equipped with power takeoff (PTO), or a powered pump that runs off the vehicle drive system.

Figure 22. Commercial water truck.


## 2.3 Materials

### 2.3.1 Geotextile

A 6-oz. needle-punched, non-woven (NP-NW) geotextile fabric was placed in the bottom of each of the excavated test craters as shown in Figure 23. The water table is very high at the test site, and the geotextile was used to separate the underlying soil from the quality backfill materials. The geotextile was cut into sheets that fit the excavated area, and two sheets were required. The second sheet was overlapped by 1 ft onto the first sheet to allow for adequate coverage.

### 2.3.2 Subgrade description

The in-situ subgrade material appeared to be a mixture of silty sand and gravel. The subgrade was not specifically characterized, but Barna et al. (2010) performed detailed testing on the same site and described the subgrade soil profile as approximately 3 in. of sandy silty gravel overlying poorly graded silty sand. Since the testing described in this report occurred in approximately the same area, it can be assumed that the subgrade materials encountered were similar to those reported by Barna et al. (2010).

Figure 23. Placement of geotextile.

### 2.3.3 Crushed limestone backfill

A crushed limestone material was used as shown in Figure 24 for the backfill of one of the test craters. The maximum aggregate size of the material was approximately 1 in.

Figure 24. Crushed limestone backfill.

### 2.3.4 Rapid-setting flowable fill

Flowable fill is a low-viscosity, grout-like, cementitious blend commonly composed of portland cement, fine aggregate, and water. Other materials such as fly ash, slag, foundry sand, bottom ash, and chemical admixtures are also commonly employed in flowable fill blends. Flowable fills can be designed for traditional and rapid-setting times, depending upon the type and amount of cementitious materials and chemical admixtures used. The material is self-leveling, self-compacting, and flows under gravity to fill all available voids.

Material properties established to accommodate rapid ADR include an unconfined compressive strength of 250 psi after 30 min of cure, 750 psi after 3 hr of cure, being optimally flowable as indicated by 8 to 12 in. of flow consistency, and exhibiting minimal shrinkage and subsidence potential. Buzzi Unicem Utility Fill 1-Step 750 is a rapid-setting flowable fill material that has been selected for rapid ADR operations due to the additional ability of being placed without the use of external mixing. After 30 min, the flowable fill possesses significant bearing capacity to accommodate construction traffic in an expedient ADR scenario.

Flowable fill is traditionally placed using the simplified volumetric mixer. This technique uniformly distributes moisture resulting in optimal flowability and achievement of ultimate compressive strength. The Buzzi Unicem 1-Step 750 can also be placed by the dry method (Figure 25). The dry method is an expedient placement technique, where the pre-blended dry material is dispensed directly into the excavation, alleviating the requirement for a dedicated mixer. Following the placement of thin lifts of dry material (4 to 6 in.), water is metered onto the surface and allowed to percolate through the dry material.

Placement using the dry method sacrifices some of the beneficial properties of flowable fill including its self-leveling behavior and up to 30% of the compressive strength. However, the material can be placed expediently without the use of additional equipment and provides sufficient bearing capacity for heavy aircraft pavement applications. The dry method was used for all test craters for the large crater test.

Figure 25. Dumping flowable fill packaged in super sacks prior to adding water, according to the dry method.

### 2.3.5 Rapid-setting concrete material

CTS Rapid Set Concrete Mix® has been selected as a rigid capping material in rapid ADR scenarios because of its high early strength and good load-carrying capacity after minimal curing time (2 hr) (Priddy et al. 2007). The main cementitious component in the mix is Rapid Set Cement®, a proprietary, calcium sulfoaluminate-based material. The aggregate within the mix is 3/8-in. maximum size pea gravel.

The dry blend of cementitious material and aggregate is stored in large 3,000-lb super sacks comprised of woven geotextile and lined with plastic. The pre-blended material requires only the addition of water, does not require the use of local aggregates, and can be mixed in a variety of concrete mixing equipment.

During the large crater test, the material was mixed using the simplified volumetric mixer. The rapid-setting concrete has a fast set time of 20 to 30 min, depending on the air temperature. Bulk citric acid can be added to the mix water to increase the working time of the material and to prevent flash setting of material within the mixer. Figure 26 shows rapid-setting concrete placement using the simplified volumetric mixer.

Figure 26. Rapid-setting concrete placed using volumetric mixer.

# 3 Team Description and Repair Process

## 3.1 Crater chief

The crater chief was responsible for accomplishing the repair objective, directing the crater repair personnel, and ensuring the quality of each repair. The crater chief is typically a junior officer or senior non-commissioned officer (NCO). During the large crater test, the crater chief drove a UTV and was also responsible for transporting equipment such as shovels, rakes, tape measures, brooms, paint, paint markers, and utility knives to the repair site and ensuring all crater repair personnel had and used the required PPE.

## 3.2 Debris removal

The debris removal team consisted of two personnel: one front-end loader operator and one CTL operator. The CTL was equipped with the bucket attachment. The debris removal team began the crater repair process by clearing the path from the staging area to the MOS and then removing debris from the test crater site. The team continued removing debris during the excavation of the repair. The front-end loader operator assisted the backfill team in preparing and leveling the natural subgrade for geotextile and backfill placement. During the repair that used crushed stone as backfill, the front-end loader was used to help spread the backfill after it was unloaded. At the end of the testing, another member of the repair team assisted in final cleanup by operating a dump truck in conjunction with the front-end loader operator. The CTL operator switched to a kick broom attachment to sweep away any small pieces of FOD generated during the repair process. Figure 27 shows the debris removal team at the beginning of the crater repair process.

## 3.3 Haul team

The haul team was responsible for continuously mobilizing the super sacks of flowable fill and rapid-setting concrete from the storage site to the repair site. Large items that were too bulky to fit into utility vehicles such as the plastic concrete forms and joint board were also transported by the haul team. The haul team consisted of three team members to operate the tractor-trailer and two forklifts, one at the staging area and one near the crater site.

Figure 27. Debris removal team operating CTL and front-end loader.


## 3.4 Marking

The marking team included three team members and two UTVs. The UTVs were used to carry the tools for marking (stanchions, tape measures, and string line) and backfilling (rakes, utility knives, flat shovels, flow meter, plate compactor). In theater, the marking team would use the stanchion method to help in identifying the crater upheaval, or crater profile measurement (CPM). Since the craters in the testing were simulated, the airmen simulated use of the stanchions (Figure 28).

Figure 28. Simulating use of stanchions for marking repair area.

Typically the marking team would mark the square crater repair area after the simulated upheaval was identified. However, since the predetermined size of the repair was to be 30 ft by 30 ft, or two slabs by two slabs, the existing joints encompassing the repair area were used as the lines of cut. The predetermined area was used to minimize damage to the adjacent slabs on the test site.

## 3.5 Saw cutting

The saw-cutting process involved four CTLs equipped with SW45 wheel saws and two spotters. All four CTLs, along with the two spotters (Figure 29), performed cuts on the large crater simultaneously, meaning each CTL cut only one line per crater. Depending upon the thickness, type of pavement, and strength of the pavement, sawing can be the slowest part of the crater repair process.

Figure 29. Saw cutting with four CTLs equipped with wheel saws and two spotters; Crater chief shown in center.


The spotters were responsible for lining up the wheel saws on the marked lines. The spotter also used a flat shovel and a push broom during the cutting process. The flat shovel was used to keep concrete debris away from the wheel saw so that the saw stayed level and flush with the PCC, and the push broom was used to sweep concrete debris so that the marked saw line was visible. The spotters were also responsible for operating the Husqvarna walk-behind saw if a backup was needed or dowel rods were encountered. Two saw team members moved to the backfill team and two to the capping team after each member had completed sawing.

## 3.6 Excavation

The excavation team was responsible for breaking up the damaged PCC within the marked crater repair area and removing the disturbed subsurface material. Three team members, two excavators, and a UTV were used during the excavation process. Two personnel were operating each of the excavators, and one spotter monitored progress. The UTV carried the spotters and tools such as tape measures, measuring stick, flat shovels, and spray paint. The spotter assisting the removal process was responsible for marking the target backfill lines inside the crater.

The Volvo HB1400 hammer on the Volvo EW180C excavator was used to break the concrete for one test crater, and the Caterpillar M318D excavator with the H120E hammer was used for the other two test craters. The excavator operator was trained to break the slab into pieces that were approximately bucket sized. The Volvo EW180C excavator with the bucket was used to remove the broken pieces and base material for all test craters. Due to the large working area, the breaking and excavating took place simultaneously as shown in Figure 30. The material in each crater was excavated to a depth of approximately 22 in. In theater, the depth of the excavation would depend on the depth of the disturbed material.

Figure 30. Breaking and excavating PCC and base material simultaneously.

## 3.7 Backfill

### 3.7.1 Crushed stone test

One test crater was constructed using crushed stone backfill material. The backfill team was responsible for filling the prepared excavation to the target surfacing depth (10 in. from the top). Crushed stone was used as a means of comparing the backfill placement time to that of the dry flowable fill method. The large size craters (30-ft by 30-ft) allowed for compaction equipment to be used, unlike the smaller-sized craters (8.5-ft by 8.5-ft), which are more suited for the flowable fill backfill.

The backfill team for crushed stone consisted of six team members including two dump-truck operators, a CTL with roller attachment operator, a front-end loader operator, and two laborers. The front-end loader operator was from the haul team, and the CTL with roller attachment was operated by an operator from the saw team. Once one saw team member had completed cutting, the saw attachment for the CTL was exchanged for the roller attachment. One dump truck operator was part of the backfill team only, while the other was originally part of the marking team. The two laborers were also originally part of the marking team. Additionally, the CTL with bucket attachment from the FOD removal team was used intermittently once FOD removal had been completed.

After the removal team had completed work, the CTL with bucket attachment was used to level the subgrade material. The backfill team laborers assisted in this operation using rakes and shovels. The CTL with roller attachment was then used to compact the subgrade. The geotextile was then applied as described previously in Section 2.3.1. After the geotextile was placed, the dump trucks loaded with crushed stone began to dump material into the excavation. The dump trucks distributed material around the crater as much as possible by dumping approximately half of their load in one location, lowering the dumping bed, and then moving to another location to dump the remaining material. The CTL with bucket attachment and the front-end loader were used to level the backfill material, along with the backfill team laborers.

Once the backfill material was somewhat level, compaction began, using the CTL with roller attachment. The small plate compactor was also used at this time to compact the edges of the repair as described in Section 2.2.8. The CTL with roller attachment made several passes until no loose

pockets of material were apparent. The material was placed in two 6-in. lifts for a target backfill thickness of 12 in.

### 3.7.2 Rapid-setting flowable fill test

For the two craters backfilled with rapid-setting flowable fill, 3,000-lb super sacks of dry pre-blended flowable fill and rapid-setting concrete were loaded on the lowboy trailer during Alarm Black, transported to the repair site, and staged near each prepared excavation. The dry flowable fill was dispensed directly into the excavation in thin (4 to 6 in.) lifts (Figure 31). The required mix water was added to the surface of the dry material (Figure 32), and the mix water was allowed to percolate through the dry material layer until little surface water was apparent. The process was repeated until the target surfacing depth was achieved. The required amount of water is specified by the manufacturer to result in a cementitious backfill with the required bearing capacity and hardening time. Mixture proportions of 50-gal of water per 3,000-lb pre-blended super sack were used during this test.

The backfill team for flowable fill consisted of six team members: two extendable boom forklift operators, one water truck operator, and three laborers. Three team members were originally from the marking team, two were originally from the saw team, and one extendable boom forklift operator was borrowed from the capping team. Equipment required for the dry-placed flowable fill included two extendable boom forklifts, a water truck, and assorted hand tools such as rakes, utility knives, shovels, measuring tape, paint, and a water flow meter. The extendable boom forklift and operator were available, since the mixer used for capping was already loaded during Alarm Black.

Figure 31. Dry flowable fill placement.

Figure 32. Water addition to flowable fill backfill.

## 3.8 Capping

The rapid-setting concrete capping team consisted of six team members including a truck driver for hauling the simplified volumetric mixer, the simplified volumetric mixer operator, a forklift operator, a water truck operator, and two laborers. The two laborers were in charge of installing the plastic forms before concrete placement as described in the next paragraph. The saw-cutting team also assisted the capping team once its mission was complete. Equipment requirements of the capping team included the simplified volumetric mixer, an extendable boom forklift, a 2,000-gal commercial water truck with 2-in. water hose, plastic concrete forms, and concrete finishing tools. The tools included shovels, rakes, magnesium screed bar, hand trowels, two empty 5-gal buckets, utility knives, 12-lb buckets of citric acid, and release agent.

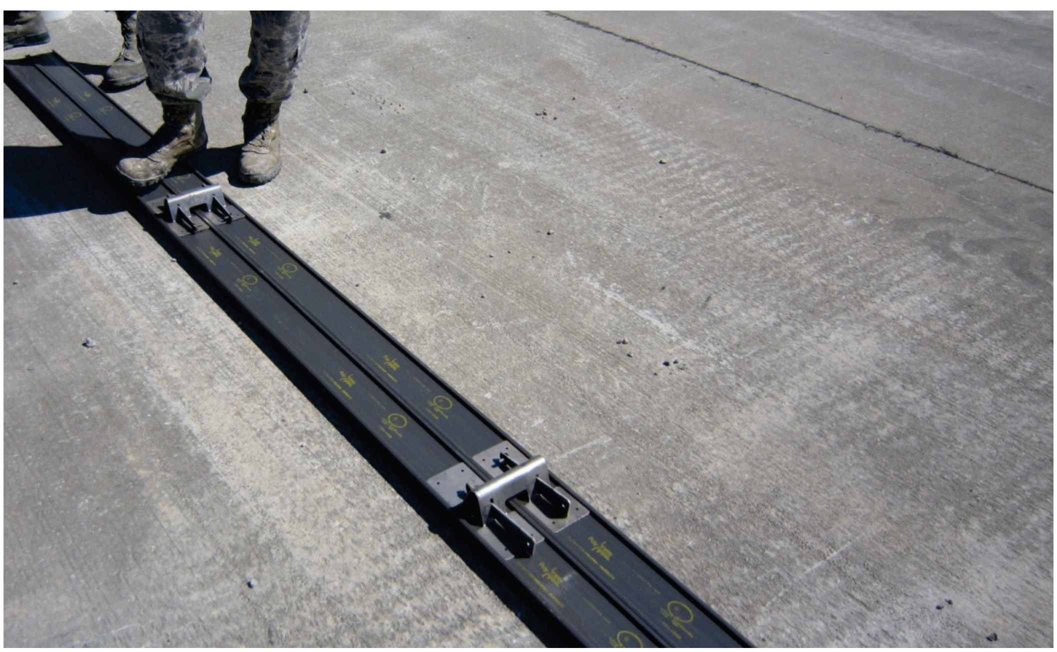
Two capping team laborers (hereafter referred to as the form team) installed the plastic concrete forms to divide the crater into quadrants for concrete placement. This step was necessary to ensure a quality repair. Due to the nature of the rapid-setting concrete, it is difficult to place large sections at one time. Installing the forms created four 15 ft by 15 ft quadrants that could each be filled with rapid-setting concrete one at a time.

Once the excavation of the crater was complete, the form team measured the length and width of the crater at the midpoints so that the plastic concrete forms could be cut to proper length using a sawzall tool (Figure 33). Each form was 4 in. tall, and two were stacked together using the stacking accessory shown in Figure 34. The stacking accessory also contains a space

for a form pin to be installed to hold the forms in place. An 8-in.-tall form was desired for the 10-in. concrete cap, so that if the backfill was placed too high, it would not result in the form protruding above the surrounding parent slab.

Figure 33. Form team cutting forms to proper length.

Figure 34. Stacking pocket accessory used for plastic concrete forms.



After that forms were cut and stacked, they were placed on top of the completed backfill, and form pins were hammered through the stacking pocket accessories as shown in Figure 35. A string line was used to ensure the forms were placed level with the surrounding pavement. The empty space beneath the forms was temporarily filled with a silt material to prevent concrete from flowing beneath the forms. Forms were placed strategically, so that once two quadrants were filled with concrete and the quadrants had achieved an initial set, the forms could be removed and no additional form work would be needed. Figure 36 shows installed formwork after the first quadrant had been placed for a large crater repair and a schematic of the order in which each quadrant was filled.

Once the first two quadrants of each repair were constructed and had achieved initial set, the plastic forms were removed and a joint board material was attached to the side of the concrete slabs to create a joint between all four of the slabs. The joint board was first applied with liquid nails adhesive, but a nail gun was later implemented since it was easier to use and worked more effectively.

Figure 35. Installation of form pins.

Figure 36. Installed formwork for one of the demo crater repairs.


The 3,000-lb super sacks of rapid-setting concrete mix were loaded on the lowboy trailer during Alarm Black (Figure 37). Initially, six super sacks of rapid-setting concrete mix were pre-loaded into the simplified volumetric mixer during Alarm Black. During the test, the rapid-setting concrete super sacks were continuously loaded into the volumetric mixer, while the mixed material was placed over the backfill (Figure 38). Citric acid in anhydrous powder form was added to the mix water tanks at a rate of 3 lb per 50 gal of water to increase the working time of the Rapid Set concrete mix. The citric acid was mixed into a slurry with a small amount of water before being added to the mix water tanks. The rapid-setting concrete cap was finished with a 16-ft-long magnesium screed bar (Figure 39) and hand tools (Figure 40). The capping TTPs specify only minimal finishing of the repair using hand tools. A bull float was used in some instances to remove large bumps in the repair. The bumps were due to a volumetric mixer malfunction, which created a concrete mix that was not fluid enough to be leveled with the screed bar.

Figure 37. Loading the simplified volumetric mixer during capping.

Figure 38. Placement of rapid-setting concrete cap with volumetric mixer.


Figure 39. Finishing using the magnesium screed bar.

Figure 40. Finishing repair edges with hand tools.

# 4 Training Procedures and Results

## 4.1 Description

Training for the large crater test consisted of both formal classroom and field instruction. ERDC project engineers briefed the airmen on the ADR modernization program as a whole, and the equipment, materials, and procedures that would be used during testing. The briefs included a review of the major ADR tasks, which include upheaval marking, sawing, breaking, excavating, backfilling, and capping processes. ERDC project engineers also presented the characteristics of the rapid-setting cementitious backfill and concrete capping materials. Safety briefs were provided to the airmen daily.

Once the classroom training was complete, the airmen were given the opportunity to become familiar with the equipment and materials used for crater repair. The field training was conducted by ERDC project engineers and technicians (Figure 41).

Figure 41. Excavator training.

Several slabs outside the test area were used to train the airmen in bomb crater repair techniques prior to formal testing. The training slabs were 15 ft wide by 15 ft long with a thickness of 9 in. An entire slab was used to simulate a medium-sized crater repair for training. Two training repairs were conducted with the assistance and guidance of ERDC engineers and technicians. Each crater repair team's processes and responsibilities were discussed during the practice craters.

During the training repairs, several of the airmen were given the opportunity to operate the Caterpillar 279C CTLs equipped with Caterpillar SW45 and SW60 wheel-saw attachments. The airmen were not experienced in operating CTLs with wheel saw attachments. Once the training was completed, the airmen who proved to be the most comfortable and efficient on the wheel saws were selected for the saw team during testing.

Experienced excavator operators were selected to break and excavate the repairs during the training and testing. The excavator operators were given time to improve their skills during training. Crushed stone was used to backfill the first training crater, while the dry flowable fill method was used for the second training crater. Figure 42 shows ERDC personnel giving the airmen crater backfill instruction.

Figure 42. Backfill training with ERDC personnel.

The simplified volumetric mixer operator was also selected before training began. ERDC project engineers and a representative from the manufacturer, Cemen Tech Inc., provided the teams with the required training to operate the simplified volumetric mixer (Figure 43). The airmen were given advice

during the capping of the practice craters to improve the quality of the repairs during the actual testing. The cap for the training craters was poured in two halves to simulate the procedures for the test craters. The form team practiced cutting the forms to the required length and installing them for both training craters. Figure 43 shows the forms in the large crater.

Figure 43. Simplified volumetric mixer training.

## 4.2 Results

### 4.2.1 Training Crater 1

Training Crater 1 was repaired using crushed stone backfill and capped with rapid-setting concrete. The airmen repaired a pre-defined 15-ft by 15-ft slab that was 9 in. thick.

The saw rate goal was 1 ft/min. Two inexperienced operators practiced using the SW45 wheel saw attached to the CAT 279C CTL. The saw-cutting rates in the 9-in.-thick PCC with the wheel saws ranged from 3.75 to 7.50 ft/min. This rate far exceeded the 1 ft/min goal, which was expected since the PCC was only 9 in. thick rather than 18 in. thick, and no dowels were present.

During this training, the airmen also learned the importance of having a wheel saw spotter and using the targets and rulers adhered to the wheel saws. The saw spotter is critical in lining up the wheel saw operator and keeping the concrete debris away from the wheel saw so that buildup

under the saw is avoided. Debris buildup decreases the efficiency of the wheel saw cutting through the concrete.

The pavement breaking and removal processes were completed with moderately experienced excavator operators. The breaker operator dropped the hammer 13 times and completed the breaking up of the 9-in.-thick PCC in 4 min. The excavator operator removed approximately 30 in. of PCC and base material in 17 min; this included repositioning the excavator a few times.

The sawing and excavation processes executed in the training slabs were timed for information purposes only; the operators were learning the equipment, techniques, and materials and were not necessarily working in the most efficient manner.

Placement and compaction of crushed stone backfill took 45 min to complete for Training Crater 1. Primary compaction was performed with the CTL roller attachment, and the edge of the excavation was compacted with the smaller plate compactor. Figure 44 displays the completed crushed limestone backfill of Training Crater 1.

Figure 44. Completed crushed stone backfill - Training Crater 1.

Capping with rapid-setting concrete took approximately 1 hr. The first half of the repair, separated using the form boards, was placed and screeded. After the rapid-setting concrete had achieved initial set, the form was stripped, and the other half of the cap was placed (Figure 45).

Figure 45. Capping of Training Crater 1.

### 4.2.2 Training Crater 2

Training Crater 2 involved the use of flowable fill as the backfill and a rapid-setting concrete cap. Two different inexperienced wheel saw operators cut the lines for Training Crater 2. The saw-cutting rates ranged from 2.14 to 5.00 ft/min. The PCC was approximately 9 in. thick. The same experienced excavator operators from Training Crater 1 were used for Training Crater 2. The operator on the excavator with the breaker attachment broke the saw cut area in 1 min, dropping the hammer six times. Repositioning once, the operator on the excavator with the bucket attachment excavated the repair to approximately 30 in. deep within 26 min. Flowable fill backfill was placed in the entire repair area in 11 min using the dry method (Figure 46). After form installation, the rapid-setting concrete cap was placed and screeded in halves as with Training Crater 1. Capping took approximately 1 hr.

Figure 46. Flowable fill backfill construction - Training Crater 2.

# 5 Test Results and Discussion

## 5.1 Layout and general description

Each simulated test crater was constructed in the middle of four slabs 15-ft long by 15-ft wide to create a 30-ft by 30-ft repair. The parent slabs ranged in thickness from 9 to 12 in., and dowels were present in the area where Crater 1 repair was conducted. Simulated craters were constructed using an excavator with the hammer attachment prior to each test. No upheaval was generated due to the nature of the crater simulation method employed; however, a large amount of debris was scattered amongst the slabs. Figure 47 shows a picture of a simulated crater. Crushed stone was used as the backfill material for Crater 1, while flowable fill was used for Craters 2 and 3. All crater repairs were capped with rapid-setting concrete.

Figure 47. Simulated large crater.

## 5.2 Weather conditions

Crater 1 was conducted on 10 Sept 2012, Crater 2 on 12 Sept 2012, and Crater 3 on 13 Sept 2012. Table 6 gives the weather conditions for each test day.

Table 6. Weather conditions during large crater testing.

| Crater # | Date | Time | Air Temperature (°F) | Wind Speed (mph) | Conditions |
|---|---|---|---|---|---|
| 1 | 9/10/12 | 900 | 73 | 6 | Clear |
| | | 1000 | 77 | 7 | Clear |
| | | 1100 | 81 | 4 | Clear |
| | | 1200 | 83 | Calm | Clear |
| | | 1300 | 84 | 7 | Clear |
| | | 1400 | 83 | 5 | Scattered Clouds |
| | | 1500 | 84 | 9 | Clear |
| | | 1600 | 84 | 5 | Partly Cloudy |
| | | 1700 | 82 | 10 | Scattered Clouds |
| 2 | 9/12/12 | 900 | 74 | 8 | Mostly Cloudy |
| | | 1000 | 78 | 8 | Scattered Clouds |
| | | 1100 | 79 | 10 | Scattered Clouds |
| | | 1200 | 81 | 8 | Scattered Clouds |
| | | 1300 | 84 | 9 | Partly Cloudy |
| | | 1400 | 85 | 8 | Scattered Clouds |
| | | 1500 | 86 | 8 | Partly Cloudy |
| | | 1600 | 84 | 8 | Mostly Cloudy |
| | | 1700 | 84 | 7 | Scattered Clouds |
| 3 | 9/13/12 | 900 | 77 | 8 | Scattered Clouds |
| | | 1000 | 78 | 9 | Scattered Clouds |
| | | 1100 | 81 | 9 | Scattered Clouds |
| | | 1200 | 84 | 5 | Partly Cloudy |
| | | 1300 | 85 | 7 | Partly Cloudy |
| | | 1400 | 87 | 6 | Partly Cloudy |
| | | 1500 | 86 | 7 | Clear |
| | | 1600 | 85 | 6 | Clear |
| | | 1700 | 84 | 7 | Clear |

Source: www.wunderground.com; Tyndall AFB, FL

## 5.3 Timeline

The timeline of each of the three crater repairs was similar, beginning with Alarm Black. During Alarm Black (1-hr period), the airmen prepared all equipment and materials for ADR operations. The airmen prepared for the crater repairs by loading materials, water, supplies, and checking fuel levels on all vehicles and equipment. Also during this time, the tractor trailer was loaded with super sacks and forms, while two dump trucks

were also loaded with crushed stone material. The equipment was staged in order of priority according to the ADR TTPs, ready to proceed with repair operations at the conclusion of Alarm Black.

Each crater repair began with the debris removal team clearing the debris away from the crater repair area. The debris removal team also removed excavated debris during the entire test as needed. The marking team began using the stanchions and marked the crater repair area as soon as the debris was removed away from each crater. Use of the stanchions was simulated, since no upheaval was present around the crater. The saw team began cutting along the delineated repairs as the haul team began unloading rapid-setting flowable fill and concrete super sacks and forms nearby but clear of the repair area. The breaking team was ready to begin as soon as all four sides of a crater were saw cut. The excavation team quickly followed suit after each crater was broken into pieces. The debris removal team cleared all material that was removed by the excavators. The crushed stone or flowable fill backfill was placed, followed by the capping of each crater as described in Section 3.8. The mix auger on the back of the simplified volumetric mixer was cleaned after each quadrant was completed to reduce buildup on the auger, which could have caused malfunction.

Soon after the repair was completed (within 2-4 hr), each crater was trafficked using a load cart that simulates one half of the landing gear of a McDonnell Douglas C-17 Globemaster III aircraft (see Section 5.4.7). Initially, 100 passes were applied to demonstrate operational capability. In the days after each repair, additional trafficking and data collection took place. Material characterization was conducted by performing heavy weight deflectometer (HWD) and dynamic cone penetrometer (DCP) testing. Distresses were measured via crack identification and collecting surface elevations.

## 5.4 Crater repair test results

### 5.4.1 Overview of repair task test times

Each portion of the crater repair process was recorded and timed. Times for each process are summarized in Table 7; these times do not include the wait times between events. A wait time occurs when one team must wait on another crater repair process to finish before work can begin. Crater 1, which utilized crushed stone backfill, took 327 min to complete, while the average repair time of Crater 2 and Crater 3, both utilizing flowable fill backfill, was 265 min.

Table 7. Task times, wait times excluded.

| Crater | Time (min) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Initial Debris Removal | Marking | Saw Cutting | Breaking | Excavating | Backfill | Capping | Total |
| Crushed Stone Backfill | | | | | | | | |
| 1 | 12 | 4 | 31 | 11 | 37 | 85 | 134 | 327 |
| Flowable Fill Backfill | | | | | | | | |
| 2 | 9 | 5 | 21 | 10 | 47 | 65 | 137 | 285 |
| 3 | 10 | 4 | 18 | 16 | 48 | 77 | 105 | 245 |
| Avg of 2 & 3 | 10 | 4 | 23 | 12 | 44 | 76 | 125 | 265 |

Gannt charts are shown in Figure 48 (Crater 1), Figure 49 (Crater 2), and Figure 50 (Crater 3). The Gantt charts provide an overview of the entire testing, including the wait times between each process. The overlap between crater repair processes can also be viewed in the Gantt charts. Overlap occurred during the repair of large craters, since the large work area enabled multiple activities to occur at once. For example, breaking and excavation frequently occurred simultaneously. For Crater 2, the extra 5 min of backfill time occurred while the capping team was completing formwork. The backfill team added a small amount of material to ensure a level backfill surface.

### 5.4.2 Saw-cutting test results

One saw team composed of four CTLs with SW45 saw attachments performed the saw-cutting operations. Each operator performed one cut, and all cutting was performed simultaneously. The saw times, cut lengths, and cut rates for each crater are displayed in Table 8. The cut rates ranged from 1.09 to 6.28 ft/min, and the average cut rate for all three craters was 2.99 ft/min. Cut rates for Crater 1 were well below average in part due to inexperience and in part due to the prescience of dowels in the parent slab. Since the dowels were older, the wheel saws were capable of cutting through them, but the cut rate was reduced. The cut rates improved as the operators gained more experience, as exhibited by the increased cut rates for Crater 2 and 3. The average of 2.99 ft/min was similar to the average of 2.94 ft/min reported by Bell et al. (2014) for the same location. The goal for saw cutting is 1.0 ft/min or more (18-in.-thick PCC). The test section concrete was much thinner and much weaker than many of the concrete pavements that will likely be encountered in the ADR scenario.

**Figure 48. Gannt chart - Crater 1.**

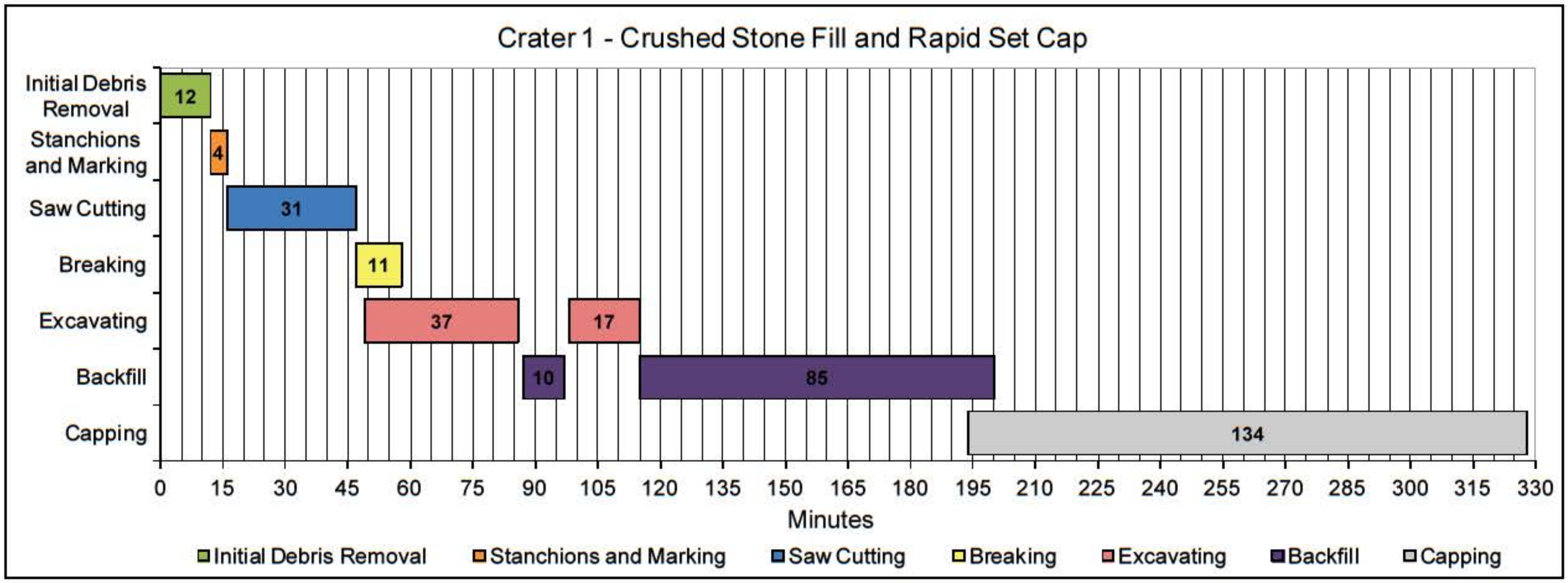


Figure 49. Gantt chart - Crater 2

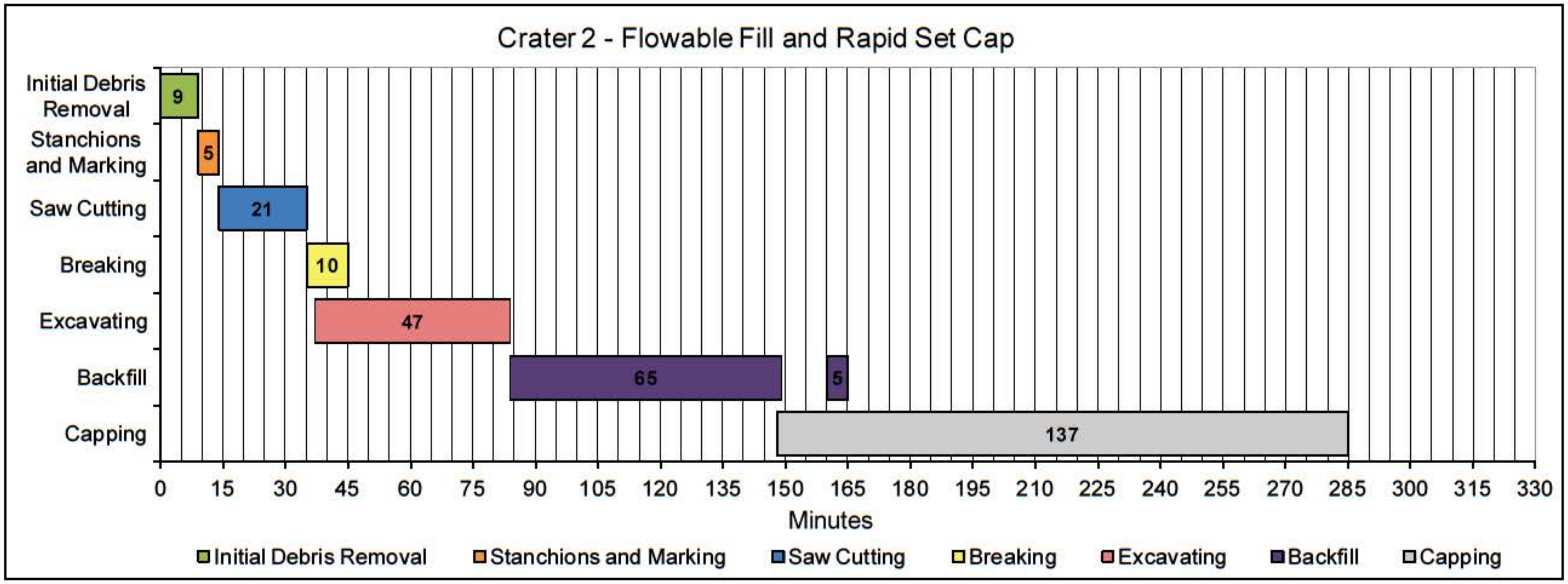


Figure 50. Gantt chart - Crater 3

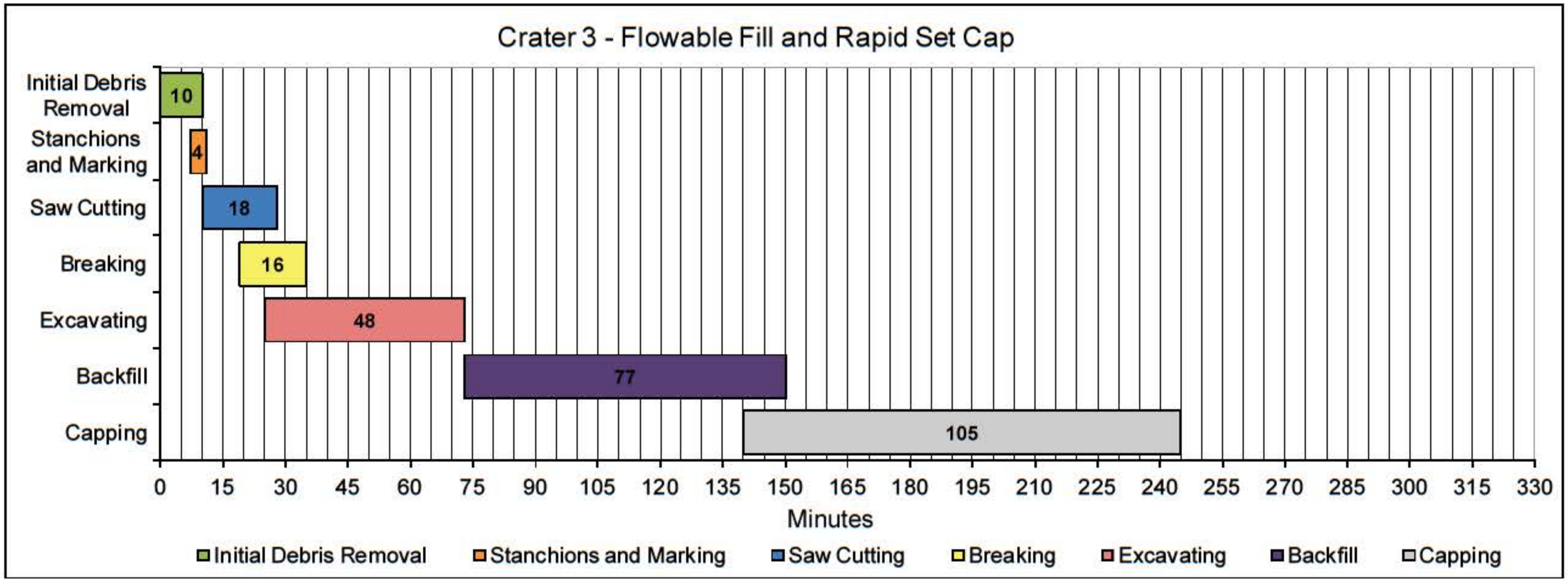


Table 8. Saw-cutting rates.

| Crater | Saw ID | Saw Time (min) | Cut Length (in.) | Cut Rate (ft/min) |
|---|---|---|---|---|
| 1 | A | 29 | 380.5 | 1.09 |
| | B | 27 | 382.5 | 1.18 |
| | C | 17 | 367.0 | 1.80 |
| | D | 29 | 376.0 | 1.08 |
| 2 | A | 9 | 371.0 | 3.44 |
| | [a]B, C | 10 | 375.5 | 3.13 |
| | C | 9 | 357.5 | 3.31 |
| | E | 8 | 380.5 | 3.96 |
| 3 | A | 13 | 372.5 | 2.39 |
| | B | 5 | 377.0 | 6.28 |
| | C | 15 | 368.0 | 2.04 |
| | E | 5 | 371.0 | 6.18 |

[a]The operator of saw C completed the saw cut for the operator of saw B.

### 5.4.3 Backfill test results

Nuclear moisture and density tests (ASTM D3017 and D6938) and DCP tests (ASTM D6951) were conducted on the crushed stone backfill layer of Crater 1 during construction as shown in Figure 51. Additional DCP testing was also conducted on the backfill after core holes were drilled to sample the concrete cap the day after testing. Table 9 contains the in-situ properties obtained from this testing for Crater 1. The dry densities obtained were lower than typical for crushed limestone (135 to 140 lbf/ft$^3$). The material was exposed to open air and had a relatively high moisture content of 14.1 %, which contributed to the lower density values. The optimum moisture content for crushed stone material for pavement base courses is typically closer to 4% according to Webster (1993). Also, since conventional compaction equipment (vibratory steel wheeled rollers) is too cumbersome to use for crater repair, the alternate equipment used (CV18 roller attachment) likely produced less compactive energy than conventional compaction equipment. The CBR values were also slightly lower than expected. Typically, well-compacted crushed stone can produce values of 80 to 100 CBR a few days after construction if the moisture content is near optimum, but the average value after construction was 45 CBR for Crater 1. However, the crushed stone backfill exceeded the strength requirement (> 25 CBR) for a subbase under rigid pavement and was acceptable for use as a backfill layer under rapid-setting concrete.

Figure 51. Crushed stone backfill data collection.

Table 9. Crater 1 backfill in-situ properties.

| Location | Dry Density (lbf/ft$^3$) | Moisture (%) | CBR (%)-during testing[a] | CBR( %)-post testing[b] |
|---|---|---|---|---|
| 1 | 120.4 | 14.1 | 10 | 30 |
| 2 | 120.4 | 14.7 | 20 | 40 |
| 3 | 119.1 | 13.6 | 50 | 70 |
| 4 | 114.8 | 13.9 | 100 | 40 |
| **Average** | **118.7** | **14.1** | **45** | **45** |

[a]Testing occurred on open backfill sections before capping

[b]Testing occurred in open core holes after completion of repair

DCP tests were conducted for Crater 2 (flowable fill backfill) after core samples were obtained, which occurred the day after each crater test. Of the three core samples obtained, two of the three resulted in refusal, indicating a CBR in excess of 100. The other test produced a CBR of approximately 75. DCP results from previous demonstrations typically indicate a CBR of 100 or greater for flowable fill (see Edwards et al. (2013) and Bell et al. (2013)). However, typically a few DCP tests will result in CBRs of less than 100, indicating an area where the material was not adequately mixed. All DCPs for flowable fill backfill did meet the strength requirement for a subbase under a rigid pavement.

### 5.4.4 Concrete cap core sample test results

Four core samples were obtained from each crater repair to verify the cap thickness and test for compressive strength at 28 days; the results are displayed in Table 10. Since the concrete cap for each crater repair was placed in four separate quadrants as described in Section 3.8, one core sample was taken from each quadrant.

Cap thicknesses for Crater 1 were 1.5 to 4.0 in. greater than the target of 10 in. The large expanse of the excavated crater made it more difficult for the airmen to ensure that the backfill was at the proper level to produce a 10-in. cap. The use of crushed stone also appeared to add to difficulty. Since the flowable fill is somewhat self-leveling, it tends to make it easier for the airmen to achieve the target backfill level. The thicknesses for Craters 2 and 3 were all within 2 in. of the 10-in. target. All compressive strengths were considerably greater than the target of 5,000 psi.

Table 10. Core sample data.

| Crater | Rapid Set Cap Thickness (in.) | Avg. Rapid Set Cap Thickness (in.) | 28-day Compressive Strength (psi) | Avg. 28-day Compressive Strength (psi) |
|---|---|---|---|---|
| 1 | 11.50 | 12.44 | 7,990 | 7,770 |
| | 12.50 | | 7,920 | |
| | 11.75 | | 6,850 | |
| | 14.00 | | 8,320 | |
| 2 | 11.25 | 10.19 | 8,410 | 8,208 |
| | 10.50 | | 8,050 | |
| | 8.50 | | 8,120 | |
| | 10.50 | | 8,250 | |
| 3 | 10.50 | 10.38 | 8,960 | 8,253 |
| | 9.00 | | 7,310 | |
| | 12.00 | | 9,110 | |
| | 10.00 | | 7,630 | |

### 5.4.5 Heavy weight deflectometer testing

The HWD was employed to collect the impulse stiffness modulus (ISM) of each repaired crater (Figure 52). One test was performed on each quadrant, and the results were averaged for each crater repair. A control test was also performed on one parent slab on site before each set of HWD testing.

Figure 52. HWD testing on repaired crater.


The ISM data from the HWD is plotted for each crater at each pass level in Figure 53. The ISMs before trafficking are considerably lower than those reported by Edwards et al. (2013) and Bell et al. (2013). Typically the ISMs for the rapid-setting concrete are between 3,500 and 4,500 kips/in. However, the measured ISMs collected at the 0 pass level ranged between 2,181 and 2,661 kips/in. The HWD data contradicts the compressive strength data discussed in Section 5.4.4, which showed that each quadrant of each crater repair exceeded the required 28-day compressive strength. For Crater 1, data was collected only at 0 and 100 passes, and the ISM increased slightly between those two intervals. Crater 2 showed a slight increase between 0 and 100 passes and then a considerable drop at 900 and 1,500 passes, as the crater repair began to fail under traffic. The ISM for Crater 3 generally remained the same until dropping moderately at 1,500 passes. The control test point showed that the PCC slab stiffness generally remained consistent. Overall, the stiffness of the repairs was generally as high or higher than the control slab, until accumulating damage from traffic.

### 5.4.6 Visual observations of concrete surface after crater repair

Each crater was photographed before trafficking began to document any cracking or other distress to the concrete surface. Several defects were noted in Crater 1. Figure 54 shows the two west quadrants of the finished crater repair. A slightly rough surface in some locations and some shrinkage cracks were noted in these quadrants. Figure 55 displays the two east quadrants of the finished crater repair. The surface of the southeast quadrant was quite rough. The rough surface was caused by the concrete mix being placed too dry, reducing its workability. Also, one track of the CTL loader from the

FOD debris removal team entered the northeast quadrant before final set was obtained, resulting in the row of track imprints, shown as the horizontal dark area in Figure 55. The plastic joint board cap on one of the quadrants was removed before final set, resulting in a small spall that ran the length of the west edge of the northeast quadrant. The small shrinkage cracks were caused by a concrete mix that contained excess water. Even a small amount of water will typically migrate to the top of the concrete cap during placement and can lead to shrinkage cracking. The variability in the concrete mix was caused by the diesel engine of the simplified volumetric mixer suddenly shutting down in several instances, to the point where a second simplified volumetric mixer was employed.

Figure 53. HWD data of large crater repairs.

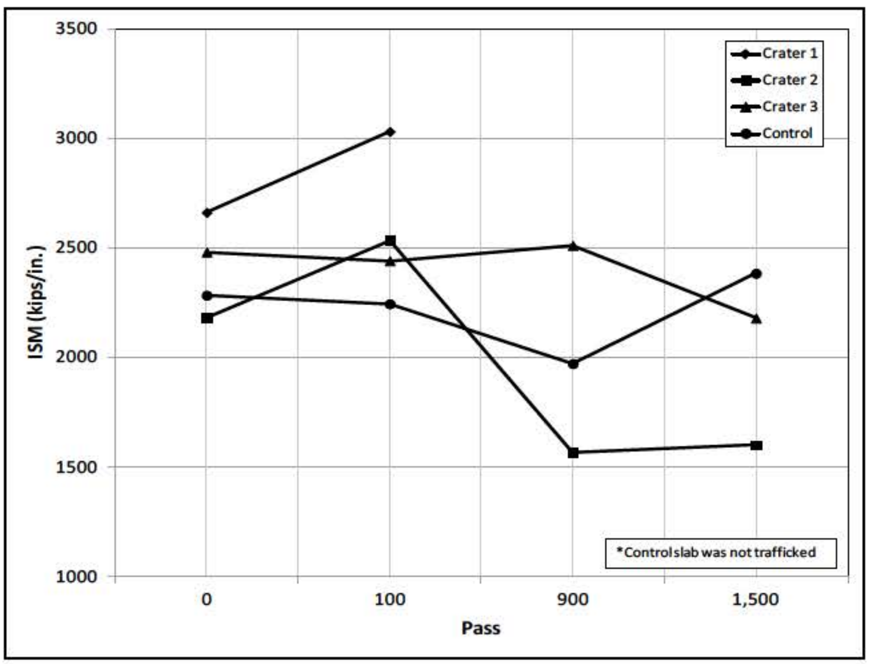



Figure 54. Crater 1, west quadrants, finished repair.

Figure 55. Crater 1, east quadrants, finished repair.

Figure 56 shows the west quadrants of Crater 2 after repair. Some shrinkage cracks (highlighted in orange) and small surface defects were noted. Figure 57 shows the east quadrants of Crater 2. Both quadrants exhibited shrinkage cracking, and the northeast quadrant contained considerably more than the southeast quadrant. Overall, the finish of Crater 2 was much smoother than Crater 1.

Figure 56. Crater 2, west quadrants, finished repair.

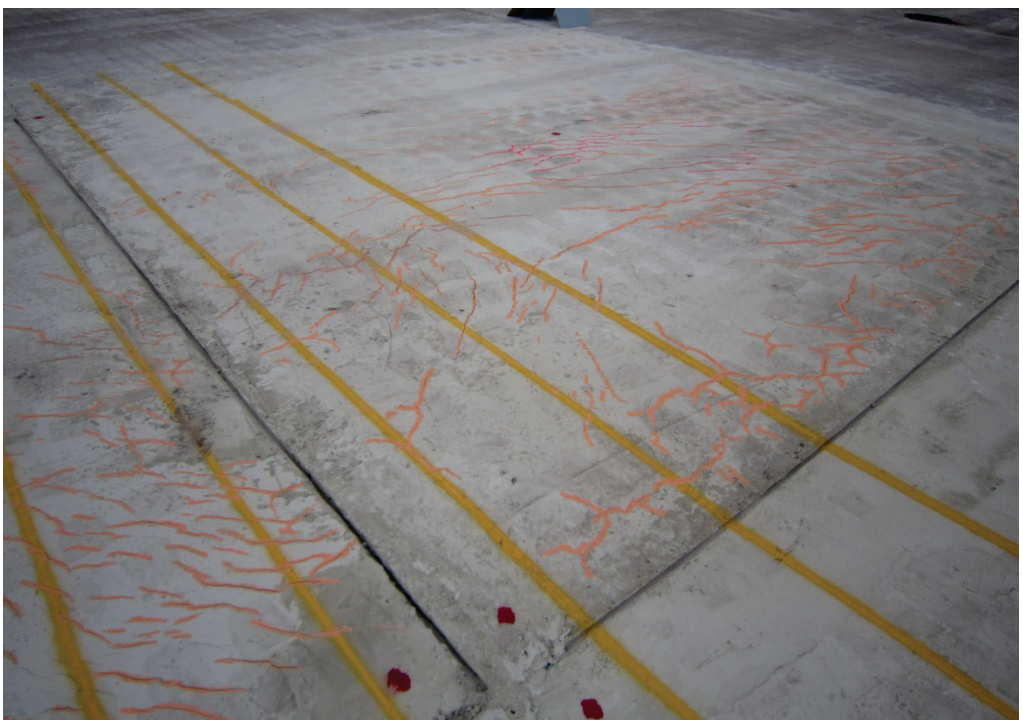
Figure 57. Crater 2, east quadrants, finished repair.

Figure 58 displays the west quadrants of Crater 3, and Figure 59 shows the east quadrants. Both western quadrants contained a considerable amount of shrinkage cracking. Also, the south edge of the southwest quadrant was not square due to damage sustained to that edge during excavation. The eastern quadrants both contained a substantial amount of shrinkage cracking. Figure 60 shows the large amount of shrinkage cracks in the northeastern quadrant.

Figure 58. Crater 3, west quadrants, finished repair.

Figure 59. Crater 3, east quadrants, finished repair.

Figure 60. Crater 3, northeast quadrant, finished repair.



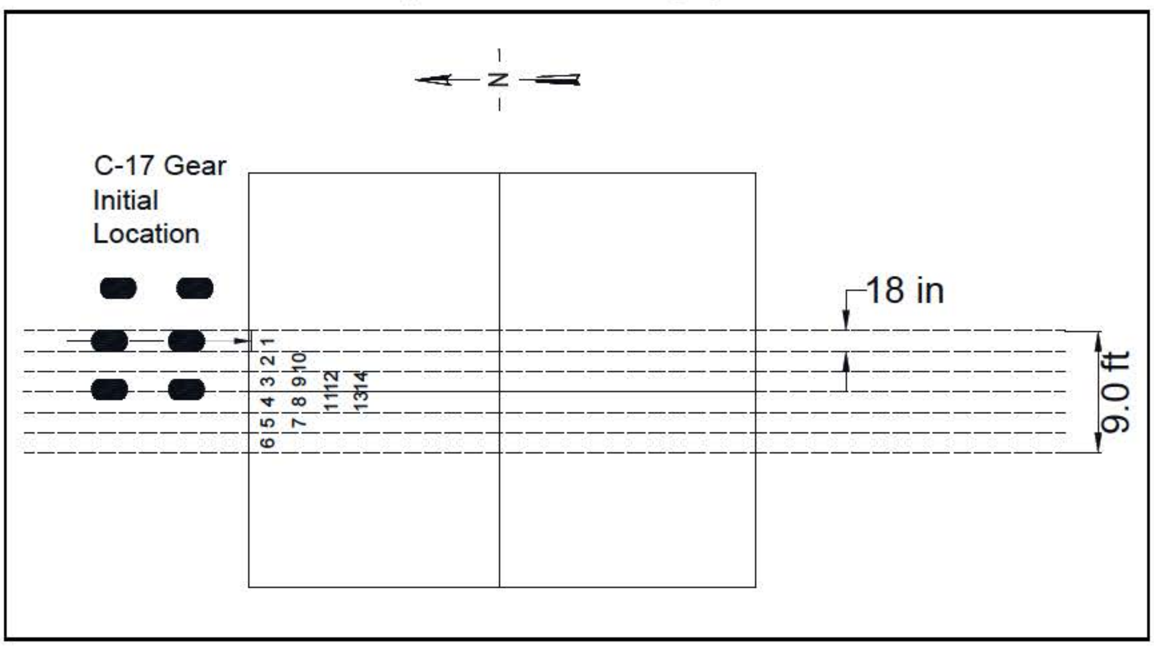
### 5.4.7 Trafficking test results

Approximately 2 hr after the completion of each crater repair, trafficking of the repair commenced using a simulated C-17 aircraft load. The multiple-wheel C-17 load cart represents one-half of the full main gear of a C-17. The multiple-wheel C-17 load cart contained six 50-in.-by-21-in., 20-ply tires inflated to 142 psi, such that the test gear was supporting 292,500 lb, which produced individual wheel loads of approximately 48,750 lb. This

configuration was used to simulate a fully loaded (585-kip) C-17 aircraft. Figure 61 shows the C-17 load cart in operation. The trafficking followed an approximated normal distribution centered on the entire crater repair as displayed in Figure 62.

Figure 61. Trafficking with full-gear C-17 load cart.

Figure 62. C-17 trafficking layout.




### 5.4.7.1 *Visual observations under traffic*

Each crater repair was initially subjected to 100 passes to ensure the crater repair met the threshold requirement for an expedient repair. After 100 passes, each crater was visually inspected for damage. For Crater 1, no new

distresses were noted after 100 passes, only those that existed after completion of the crater repair. After 200 passes, several low-severity longitudinal cracks were observed, along with one corner spall and a corner break. Since these were low-severity distresses, trafficking continued. After 400 passes, the longitudinal cracks had expanded to produce a medium-severity shattered slab, as shown in Figure 63. The slab was broken into four pieces with cracks from 1/8 in. to 1 in. wide. The corner spall and corner break were also medium severity, and Crater 1 was considered failed after 400 passes.

Figure 63. Crater 1, 400 passes, shattered slab in southwest quadrant.

After 100 passes were applied to Crater 2, no new distresses were observed. At 200 passes, small, low-severity longitudinal cracking (< 1/8 in. wide) was apparent, and these cracks grew to medium-severity (1/8 in. to 1 in. wide) after 400 passes. At 900 passes, more of the medium-severity cracks began to connect, particularly on the southeast quadrant near the intersection of the four quadrants as shown in Figure 64. In addition, some delamination of a ½-in. layer in the traffic lane produced FOD potential as shown in Figure 65.

At 1,500 passes, the cracking shown previously continued to propagate, and more delamination occurred as shown in Figure 66 and Figure 67, respectively. Crater 2 was considered failed at 1,500 passes.

Figure 64. Crater 2, 900 passes, medium-severity cracking.

Figure 65. Crater 2, 900 passes, high-severity joint spall.

Figure 66. Crater 2, 1,500 passes, medium-severity longitudinal cracking.

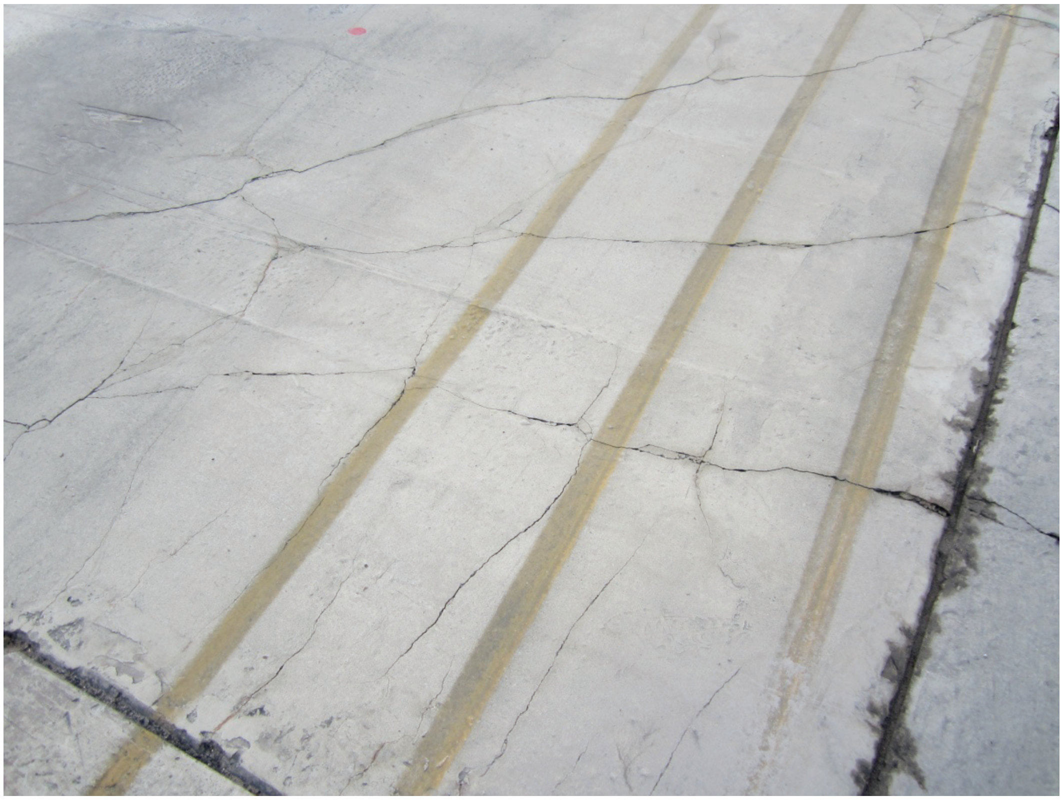


Figure 67. Crater 2, 1,500 passes, high-severity joint spall.

For Crater 3, the only new distress observed at 100 passes was some spalling along the joint that was perpendicular to traffic in the southwest quadrant as shown in Figure 68. The spalling was likely caused by a small amount of concrete that was placed to fill the void created during excavation, as discussed in Section 5.4.6. After 900 passes, a low-severity corner break and low-severity longitudinal cracking were noted. The spall shown in Figure 68 continued to produce FOD, but the joint was kept clean during trafficking. Trafficking continued, since this was not considered a structural failure and could be sustained by normal sweeping of the runway surface.

Figure 68. Crater 3, 100 passes, medium-severity joint spall.

After 1,500 passes, several distresses were observed. Two medium-severity corner breaks were noted near the point where the four quadrants intersect. The joint spall previously mentioned continued to produce a large amount of FOD, and a deep joint spall was observed in the northwest quadrant as shown in Figure 69. Due to signs of structural failure and possible tire hazards, Crater 3 was considered failed at 1,500 passes and trafficking ceased.

### *5.4.7.2 Surveying measurements*

Each crater repair was surveyed before traffic was applied and at pertinent traffic levels to measure elevation changes due to cracking or spalling. Survey points were located on a square grid with 1-ft spacings for a total of 900 survey points for each 30-ft-by-30-ft crater. The elevations were determined by using a robotic total station. The maximum increases and decreases in elevation for each crater at various pass levels are displayed in Table 11.

Figure 69. Crater 3, 1,500 passes, high-severity joint spall.

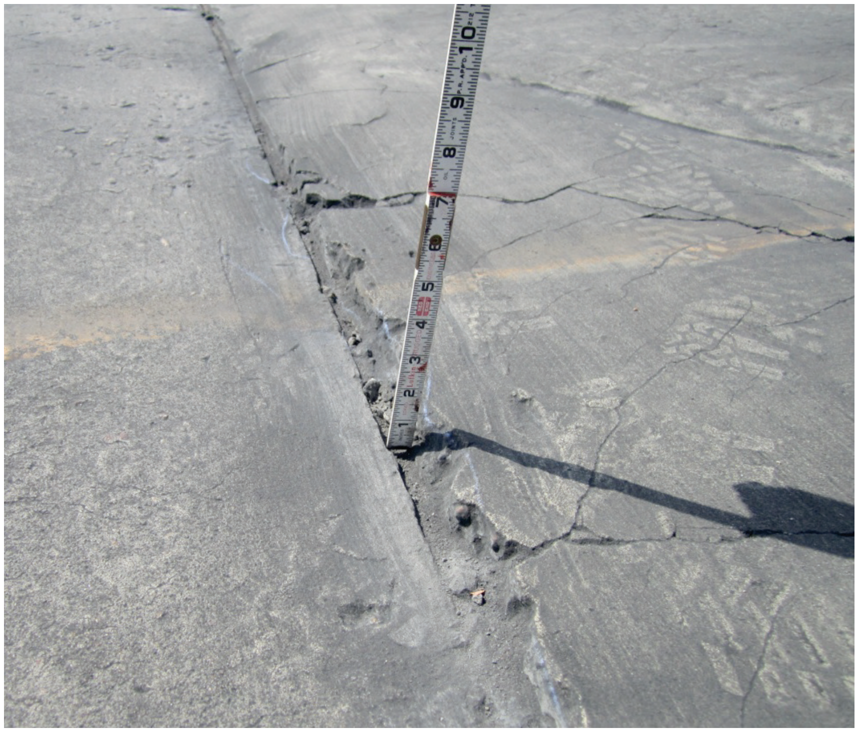


Table 11. Elevation changes for each crater by pass level.

| Crater | Number of Passes | Maximum Decrease in Elevation (in.) | Maximum Increase in Elevation (in.) | Average Elevation Difference (in.) |
|---|---|---|---|---|
| 1 | 100 | 0.07 | 0.43 | +0.14 |
| 2 | 100 | 0.52 | 0.19 | -0.01 |
| | 900 | 4.03 | 3.96 | -0.22 |
| | 1,500 | 4.40 | 3.86 | -0.31 |
| 3 | 100 | 0.26 | 0.16 | +0.01 |
| | 900 | 0.85 | 0.22 | -0.19 |
| | 1,500 | 0.98 | 0.11 | -0.23 |

For Crater 1, measurements were taken after 100 passes, and the maximum permanent deformation measured was 0.43 in., indicating only a small deformation. Crater 1 was considered failed after 400 passes due to a shattered slab. Surveying measurements were not recorded at 400 passes.

For Crater 2, after 100 passes, the maximum permanent deformation recorded was 0.52 in. However, after 900 passes, the maximum permanent deformation jumped to 4.03 in. with a maximum increase of 3.96 in. Survey results were not analyzed until after the completion of trafficking, and these drastic changes in elevation were not apparent upon visual inspection.

These results are believed to be erroneous and, therefore, were not considered during failure assessment of Crater 2. Since no tire hazards or large changes in elevation were visually apparent, trafficking continued for Crater 2. Results of Crater 2 after 1,500 passes were similar to those obtained after 900 passes. The maximum permanent deformation was 4.93 in., while the maximum increase in elevation was 3.86 in. at 1,500 passes. The average change in elevation was a decrease of 0.31 in.

Crater 3 showed a maximum decrease in elevation of just over 0.25 in. after 100 passes and just over 0.75 in. after 900 passes. At failure (1,500 passes), the maximum deformation increased to 0.98 in. Increases in elevation were all below 0.25 in. for all pass levels. The higher decreases in elevation were located near the joint between the two southern slabs and the adjoining parent slabs. The decrease in elevation was expected, since a thin layer of repair material was placed there as discussed in Section 5.4.6. The material began to spall and was swept away during intervals between data collection.

# 6 Conclusions and Feedback

The main objective of the large crater repair test was to ensure that technologies developed under the ADR Modernization program for small (8.5 ft by 8.5 ft) craters could be used for larger (30 ft by 30 ft) repairs. The following section presents the conclusions determined from the large crater repair tests.

## 6.1 Conclusions

- The damage delineation, upheaval and disturbed material removal, were not affected by the increase in size of the repairs other than an expected increase in time required to complete these tasks due to the size of the craters.
- The crushed stone backfill time was an average of 14 min slower than flowable fill backfill time.
- The crushed stone backfill strength, as measured by DCP tests, was considerably lower than the flowable fill backfill strength but met strength requirements. Since the crushed stone moisture content was higher than optimum, it is recommended to closely monitor the moisture level of crushed stone stockpiles that are to be used for crater repair.
- The crushed stone backfill elevation should be monitored more closely, so that the resulting cap thickness will be as close to the target at possible.
- The flowable fill backfill and rapid-setting concrete material met the strength requirements for crater repair.
- The method used to place the rapid-setting concrete in four sections was successful.
- The repairs using flowable fill backfill were able to sustain 1,500 passes of the fully loaded C-17 load cart, but with considerable damage indicating a structural failure mode. Additional backfill and/or cap thickness may be required to sustain a higher number of passes of a fully loaded C-17.
- It is recommended that the required backfill and cap thickness be determined analytically and another field test be conducted to validate the results.

## 6.2 Troop feedback

The airmen (Prime BEEF and Red Horse) provided feedback to the ERDC engineers after each day of testing. The following list summarizes their recommendations.

- The saw operators suggested having one spotter per saw (four total) instead of one spotter for two saws (two total).
- A longer extension chute was suggested for the volumetric mixer when performing large crater repairs.
- The chute on the volumetric mixer should have vibrators attached to make washout easier.
- The capping team suggested using a different screed that is easier to grip during the screeding process.
- The adhesive used to attach the joint board should have a faster set time, or the nail gun should be used exclusively.

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Geotechnical and Structures Laboratory
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**12. DISTRIBUTION / AVAILABILITY STATEMENT**

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**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

The inability to effectively operate both fighter and heavy cargo aircraft on the same repaired runway after an attack poses significant operational challenges. The U.S. Air Force Air Combat Command (ACC) began the Airfield Damage Repair (ADR) Modernization Program to develop technologies to address operational limitations of current ADR equipment, material, and tactics. The objective of the program was to modernize the Air Force's ADR capability through development of new ADR solutions that are suitable for both fighter and cargo aircraft while scalable to the threat or damage. These solutions were successfully demonstrated as a part of the Critical Runway AssessmenT and Repair (CRATR) Joint Capabilities Technology Demonstration (JCTD) Program for small (8.5 ft by 8.5 ft) crater repairs. This report describes the use of new ADR technologies for repairing large (30 ft by 30 ft) craters at the Silver Flag Exercise Site in Tyndall Air Force Base, Florida. Modernized ADR technologies were successfully demonstrated in a series of three different large crater repairs. Two repairs utilized flowable fill backfill, while one used a crushed stone backfill. The repairs conducted using flowable fill backfill withstood 1,500 simulated C-17 aircraft passes before reaching failure, while the repair backfilled with crushed stone failed at 400 passes.

**15. SUBJECT TERMS**

Airfield Damage Repair
Large Craters
Rapid-setting Concrete
Flowable Fill

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